IMPACTS OF WOODY DEBRIS ON FLUVIAL PROCESSES AND CHANNEL MORPHOLOGY IN STABLE AND UNSTABLE STREAMS

by

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SUMMARY

This report documents the findings of a 3 year study to asses the impact of Large Woody Debris (LWD) upon channel evolution and morphology in unstable sand bed rivers in northern Mississippi. The aim of this research is to gain an improved understanding of the basin-wide impact of LWD dynamics in unstable and stable channel environments and to develop a set of coherent debris management strategies for erosion control, habitat enhancement, and maintenance/design considerations for run-of-river structures, based upon sound geomorphic and engineering analysis.

Data from the US Army Corps of Engineers Demonstration Erosion Control (DEC) survey program, conducted in May 1995, was used to locate significant debris jams with respect to planform and long profile data on 23 river reaches in northern Mississippi. The reaches surveyed are between 4000 and 12000 feet long and range in upstream basin area from 3.5 to 150 square miles. A comprehensive understanding of debris dynamics can be established by surveying these channels because the reaches fall into several categories including, stable/unstable reaches, straight/meandering reaches and reaches which have either a predominantly agricultural or wooded riparian zone. The debris jams in each reach were surveyed in detail to determine the mechanisms and locations of debris input, jam impact upon channel morphology and sediment routing and jam stability over time. The last of these objectives was assessed by comparing the survey results of the current study with those obtained in a 1994/1995 research project (see Wallerstein & Thorne, 1995).

An up to date review of the literature concerning the geomorphic impacts of in-channel LWD, and current LWD management strategies is presented.

A conceptual debris jam classification model is presented, based upon 'key' debris dimensions relative to channel width and found to correspond well with the field data. This model also explains the spatial distribution of sedimentation and scour processes associated with debris jams. Results show that the net balance between debris induced sediment retention and debris induced channel scour is in favour of sedimentation, indicating that debris jams help to accelerate sedimentation processes in these channel systems. Comparison of survey results between summer 1995 and summer 1996 shows there to be little change in the number and position of debris jams present in each reach. It appears, therefore, that debris jams are stable features in the short-term, although a better understanding of jam longevity can only be achieved through a long-term monitoring program.

The LWD Management Program (DMP) has been tested and improved based upon the new findings. The Debris at Bridge Pier Prediction Program (DBP3) has also been improved and now calculates the pier scour adjustment factors, whereas these had to be entered by hand in the previous version.

Both the DMP and DBP3 programs, and user manuals (written in MS Word ver. 7) are enclosed, inside the rear cover of this report.

The GIS user interface for the DMP is also now available for use and can be obtained upon request from nick@geography.nottingham.ac.uk

The program runs on the UNIX version of ARC INFO and requires approximately 98 mb of memory to install.

Final conclusions regarding the management of LWD in unstable channel systems are made based upon the results of this three year research program.

UNITS OF MEASUREMENT

Units of measurement used in this report can be converted as follows:

To convert	To	Multiply by
inches (in)	*millimetres (mm)*	25.4
feet (ft)	*meters (m)*	0.305
yards (yd)	*meters (m)*	0.914
miles (Mi)	*kilometres (km)*	1.61
square miles (sq. miles)	*square kilometres (km^2)*	2.59
cubic feet per second (cfs)	*cubic meters per second (cms)*	0.0283

ACKNOWLEDGEMENTS

We should like to offer special thanks to the following people and organisation for their assistance with this research effort. Mike Trawle and Frank Neilson for supporting and facilitating the funding of this research and for their technical and logistical assistance. The US Army Corps of Engineers (WES). Jerry Comati at theUS Army Research, Development and Standardization Group, UK, for authorising, and funding this project. Finally, but by no means least, Chester Watson, Chris Thornton and all the members of the Colorado State University DEC field survey crew for their continuing and invaluable assistance with fieldwork and data collection in northern Mississippi.

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1 INTRODUCTION

There has been increasing interest in the role of vegetation in fluvial geomorphology in recent years because it has been recognised that river dynamics cannot be fully understood without taking into account the impact that vegetation has upon bank stability, flow velocity, and riverine habitat.

As a consequence, the study of in-channel Large Woody Debris (LWD) or Coarse Woody Debris (CWD) as it is sometimes referred to (that is trees, branches and other larger organic matter, operationally defined as material with a length greater than 1 metre) and its accumulation as jams or dams and impact upon the channel environment have become topics receiving increasing research interest over the past 5 to 10 years.

In a review of relevant literature undertaken in an earlier study (Wallerstein 1994) it was established that a large proportion of the research performed to date has been carried out in upland areas, and in stable, gravel bed rivers such as in the Pacific North West (Hogan et. al., 1995; Fetherston et. al.; 1995) to determine the impact of LWD on salmon habitat and migration, and in relation to logging operations and forest management. Very little is known about the impact of LWD in unstable or sand bed rivers. Much of the work is fairly qualitative and observational in nature and there has been little emphasis on determining the key variables at play in LWD dynamics, and the modes of their interaction. Most studies have also been undertaken in isolated reaches, rather than covering basin-wide debris processes, although there are one or two notable exceptions (see Gregory et al., 1993).

At present, LWD management is, therefore, conducted from an incomplete understanding of debris impacts and dynamics and operational maintenance of debris is carried out on an *ad hoc* basis.

The aim of this research effort has been to asses the catchment wide impact of LWD over a wide range of channel sizes in unstable, rapidly evolving rivers with sand, clay and loess bed and banks. The research in this project has been centred on streams in the DEC (Demonstration Erosion Control) watersheds draining the Bluff Line hills of Northern Mississippi, which are known to be evolving rapidly in response to complex response in the fluvial system following catchment land-use changes and past engineering interventions.

The specific aims of this research are:

1) To collect a large, representative data set concerning the reach scale and basin-wide influences of LWD on channel morphology in a different type of channel environment to that

which has been studied to date: specifically, in unstable, rapidly evolving sand-bed rivers.

2) To assess whether there are preferential sites of debris input and accumulation within the channel environment and investigate the stability of debris jams in term of their longevity in a given reach.

3) To investigate how effectively debris jams inhibit or promote bed scour, sediment transport and storage to determine whether they are net stabilising or destabilising elements in the fluvial system.

4)To assess the impact of debris at run-of-river hydraulic structures such as grade controls, bridges, bendway weirs, locks and dam sluices.

5) To develop a set of guidelines for in-channel LWD management that can be used by engineers and river managers as an aid to assessment, design and maintenance of stable channels.

6) To develop guidelines for LWD management technologies at run-of-river structures.

This report presents state-of-the-art review of literature concerning the geomorphological impact of LWD and LWD management strategies.

Data collection was initiated through a three week survey program in May 199[illegible] with the assistance of the Colorado State University DEC monitoring project survey crew. A comprehensive reconnaissance survey was made of all debris jams in the 23 study reaches and each site was also surveyed to gather the long profile and cross section data needed to enable comparison with the data obtained in an earlier survey of May 1994. Analysis of these data is include in this report.

The geomorphological characteristics of jams in each reach have been analysed and plotted against independent catchment variables including drainage basin area, stream power and average channel top width, to determine whether the geomorphological effects of LWD have a coherent and predictable spatial relationship. Debris jam sediment budgets have also been calculated and related to spatial parameters to determine whether the net impact of debris jams is through sediment retention or sediment scour and mobilisation. An understanding of this impact is important as it indicates whether LWD is a net stabilising or destabilising agent in unstable, sand-bed rivers.

The long-term aim of this research is to improve understanding of the basin-wide impacts of LWD in unstable and stable channel environments, and to develop coherent, basin-wide debris management strategies for erosion control and habitat enhancement and to propose new

maintenance/design procedures for DEC and run-of-river structures, based on sound geomorphic and engineering analyses. The report presents final conclusions regarding the management of LWD, based upon the results of this three year research program.

Both the DMP and DBP3 programs, and user manuals (written in MS Word ver. 7) are enclosed, inside the rear cover of this report
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2 LITERATURE REVIEW

2.1 INTRODUCTION

Organic or woody debris is an important channel independent variable in many fluvial systems (Hogan, 1987). For example, Bevan (1948; quoted in Keller and Macdonald, 1995) concluded that in the Middle Fork Willamette River, Oregon, woody debris was responsible for more channel changes than any other factor.

In a literature review of published material then available, Hickin (1984) suggested that vegetation may influence channel processes through five mechanisms:

a) Flow resistance

b) Bank strength

c) Bar sedimentation

d) Formation of log jams

e) Concave-bank bench deposits

Hogan also identified that the literature concerning this subject was of two main types: that dealing with the indirect influence relations between vegetation, water, sediment yields and river morphology; and that dealing with the direct impacts of channel vegetation on channel morphology.

Since the 1980s the number of papers dealing with vegetation in rivers has increased markedly, however, including a number of studies concerning Coarse Woody Debris (CWD), (Nakamura & Swanson, 1993), Large Organic Debris (LOD) (Hogan, 1987) or Large Woody Debris (LWD), (Smith & Shields, 1992) and its accumulation as jams or dams in river channels.

Studies can be grouped by topic into those dealing primarily with:

a) Input processes, distribution and residence time of LWD

b) Geomorphic significance of LWD

c) Ecological impact of LWD

The physical processes involved in each topic vary depending upon the size of the stream relative to that of the CWD (Nakamura et al, 1993).

Most studies have been carried out in essentially stable channel environments in the US and Canadian Pacific Northwest, UK, and New Zealand. Instability, in the form of landsliding, is cited by Pearce & Watson (1981) as a means for debris to enter channels, but, more generally, the study of debris impacts in inherently unstable channels has not been addressed.

2.2 INPUT PROCESSES, FORMATION AND RESIDENCE TIME OF LWD

2.2.1 Input Processes

Large Organic Debris enters river systems by two main processes; either from outside the channel due to bank erosion, mass wasting, windthrow, collapse of trees due to ice loading or biological factors such as death and litter fall (Keller, 1979); or from inside the channel, through erosion and flotation of emergent and riparian trees (Hogan, 1987) (Figure 2.1). Fetherston et al. (1995) suggest that debris inputs are either "chronic or episodic". Chronic inputs are frequent, but small in magnitude and occur due to tree mortality and bank failure. Episodic inputs are infrequent, but provide a large amount of material. Episodic input processes include windthrow, ice storm, fire and flood events. The dominance of different input processes varies widely. For example, 45 percent of input is due to windthrow in the Lymington Basin, UK (Gregory et. al, 1993), while massive inputs from landsliding of debris in a mountain catchment are reported by Pearce & Watson (1983) and by lansliding as a consequence of logging operations in the Queen Charlotte Island, British Columbia by Hogan et al. (1995). Keller et al. (1979) suggest that in low gradient, meandering streams inputs are predominantly the result of bank erosion and mass bank wasting, windthrow and ice loading, while in mountain streams the main process is debris avalanche. Diehl & Bryan (1994) found the dominant input process to be bank erosion in unstable rivers in Tennessee and noted that channel instability could be a good indicator of in-channel debris abundance. LWD that has been input by bank erosion can be identified and distinguished from that which has entered by other processes because the trees will usually have an asymmetrical root mass due to progressive slipping of the tree from the bank into the channel (Diehl & Bryan, 1994). Smith et al. (1993) found debris input to be spatially random. However, the locations of zones from which LWD is supplied will vary as a function of the distribution of riparian vegetation, streamside topography, channel characteristics and the prevailing wind strength and direction, (Fetherston et al., 1995). It may, therefore, be possible to determine which are the dominant input factors based on observations of these factors and, thereby, predict the distribution of major source areas within the catchment.

2.2.2 Formation of Jams

Once in a channel, debris may form into jams or dams. Jams usually form around "key coarse woody debris" (Nakamura, 1993), which are usually large, whole trees that have entered the channel by one of the mechanisms mentioned above and which may be anchored to the bed or banks at one or both ends. Smaller debris floating down the channel then accumulates against

the key elements, which act as a sieve to debris and, later to sediment. If there is no fine debris in the stream a mature jam may never form, so that the impact of key-debris is minimal. The location of debris jams within the channel, their size and their coherence vary as functions of position in the catchment. In small streams much debris will accumulate where it falls because the flow is not competent to move coarse material and it is in larger streams that distinct jams may form. In yet larger rivers debris may never accumulate because it is carried away downstream. Piegay (1993) observed debris distribution in a sixth-order river in France and found that most material was deposited on the channel margins, forming a narrow debris line rather than in-flow jams. Wallance & Benke (1984) noted a similar distribution in meandering rivers in the southeast USA where dense, partial jams formed at a angle to the main flow. As mean channel dimensions and flow competence increase downstream more and more debris will be moved from its position of input, until all but the largest trees are transported. This process relationship may result in a trend of reducing LWD frequency downstream but, at the same time, produce an increase in the volumetric size of each jam (Swanson et. al., 1982).

2.2.3 Residence time of debris jams

The residence time, or persistence, of debris jams is an important factor, which determines the timespan over which channel morphology at a jam site will be affected. The influence exerted by jams on channel morphology also varies with time as the debris in the jam structure deteriorates (Hogan et. al., 1995). Assessing residence time is difficult and estimates range between 12 months for a 36% change or removal (Gregory & Gurnell (1985), to 40-90 years (Hogan, 1987), to 200 years for streams in British Columbia (Keller & Tally, 1979). Residence times may vary as a function of drainage basin area, and are largely dependent upon the return period of a flood with a magnitude capable of entraining a significant proportion of the trapped debris or moving larger key components of the jam. Other important factors affecting jam persistence are average tree dimensions and wood deterioration rate. Swanson et al. (1982) discovered that the density and volume of in-channel debris are greater in rivers which flow through coniferous forests, than they are in rivers that flow though deciduous forests. This is because conifers are, on average, taller and have slower decay rates than deciduous trees.

Figure 2.1 Dynamics of woody debris (adapted from Keller & Swanson, 1979)

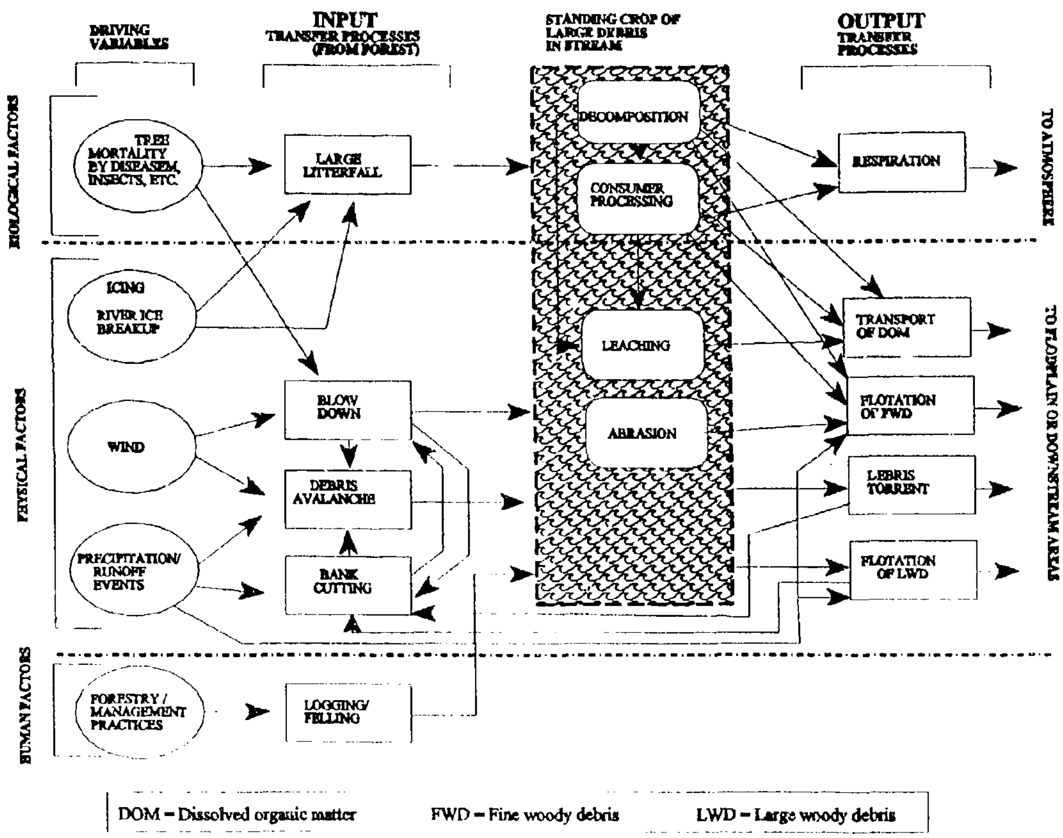
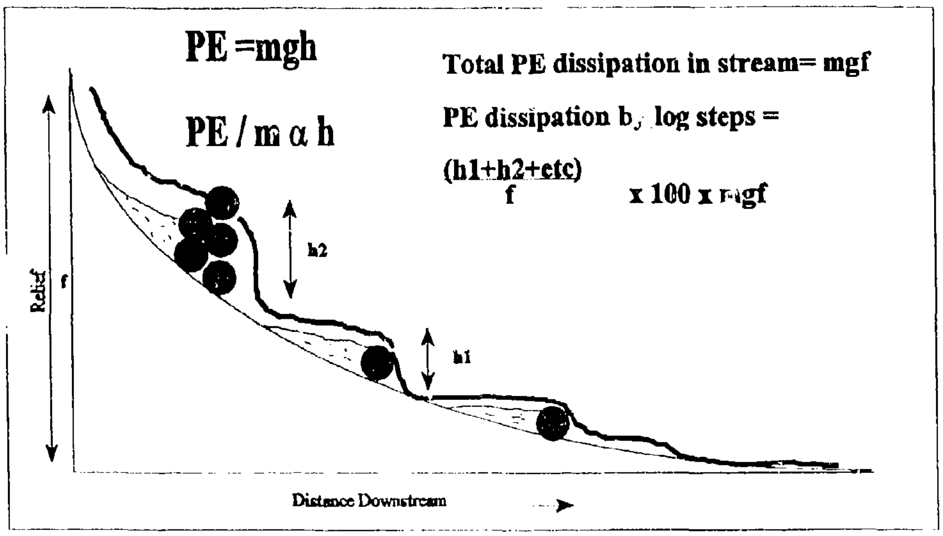
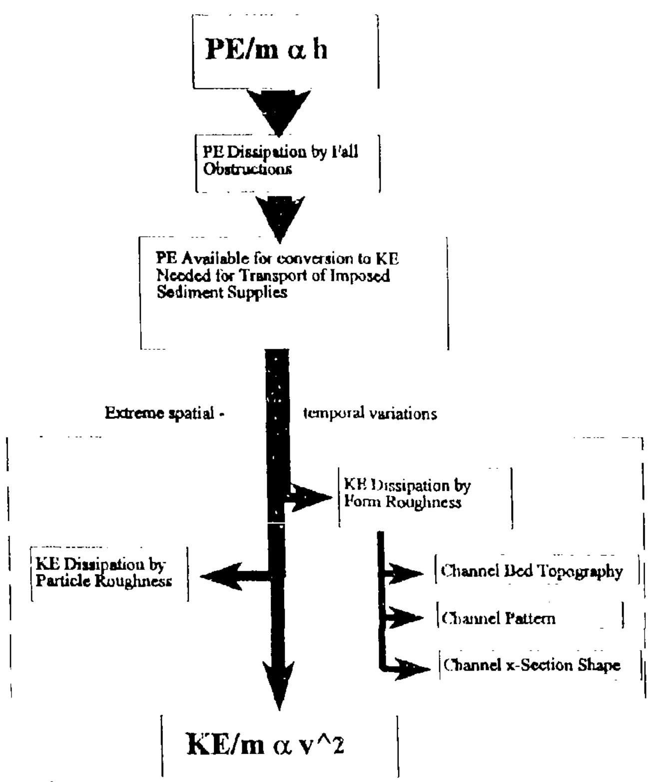


Figure 2.2 Energy transformations in streams with log steps (adapted from Marston, 1982)



Potential stream energy per unit mass of water (PE/m) is directly proportional to h, or the relief in a specific stream.
PE dissipation by log steps = Cumulative change of water surface elevation (h1+h2+ etc) as a percentage of total stream relief (f)



Log steps cause a reduction in potential energy that would otherwise be converted to a longitudinal component of kinetic energy actually used for sediment transport (PE/m = potential stream energy per unit mass of water; KE/m = kinetic energy per unit mass of water; h = relief in a specific segment; v = stream velocity

2.3 GEOMORPHIC SIGNIFICANCE OF LWD

2.3.1 Effects of channel scale

It is important to recognise that processes are scale-dependent and that the influence of LWD on channel and valley morphology may change systematically downstream through the network (Abbe & Montgomery, 1993). Zimmerman et al. (1967) found that debris accumulations in a very small stream completely obscured the usual hydraulic geometry relations, while Robinson & Beschta (1990), and Keller & Tally (1979) suggest that debris loadings increase with stream size. Gregory et al. (1985), have characterised jams into three types :

1) Active (form a complete barrier to water and sediment movement, and create a distinct step or fall in the channel profile)
2) Complete (a complete barrier to water/sediment movement, but no step formed)
3) Partial (only a partial barrier to flow)

They suggest that these types become more prevalent sequentially as channel size increases.

Once trees fall into a stream, their influence on channel form and process may be quite different to that when they were on the banks, changing from a stabilising to a destabilising influence due to their effect in causing causing local bed scour and basal erosion of the banks. Thus, jams represent a type of auto-diversion, that is a change in channel morphology triggered by the fluvial process itself (Keller & Swanson, 1979).

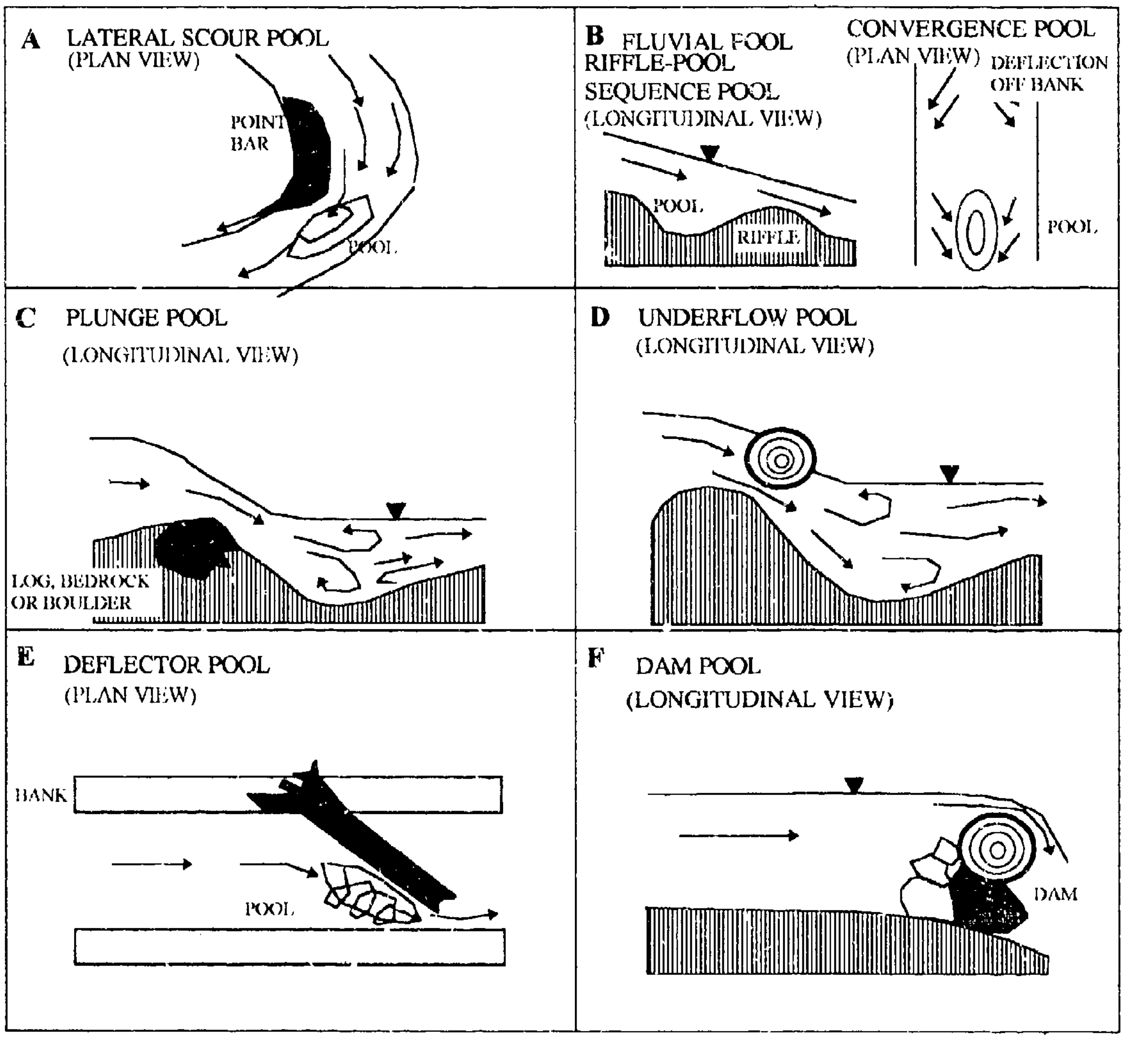
The type and degree of impact on channel morphology depends primarily on the channel width/tree height ratio and on debris orientation relative to the flow. Mean discharge and the dominant discharge recurrence interval are also important because the higher the flow is relative to jam size, the smaller will be the jam's impact through flow diversion and channel roughening. The principal effects of debris upon channel morphology are described below.

2.3.2 Impact of debris jams upon channel morphology

LWD influences the geomorphology of rivers at three levels (Gray, 1974): the overall channel form; detailed features of the channel topography; and, channel roughness.

Heede (1985), Smith (1993), Andrus et al. (1988) and Mosley (1981) have all observed that the spatial distribution and number of pools, riffles and gravel bars is positively related to the distribution and volume of LWD in the channel. This relationship has been explained through laboratory experiments by Smith & Beschta (1994), who found that the pool-riffle sequence in

Figure 2.3 Schematic diagrams of pool types (Modified from Robinson and Beschta, 1990)



gravel-bed rivers is maintained by a combination of mean boundary shear stress and intermittent lift and drag forces due to velocity fluctuations around debris. Random debris input will also distort the pool-riffle sequence, making it less systematic, so that the long-profile has very little spatial memory or periodicity (Robinson & Beschta, 1990). Robinson and Beschta (1990) devised a pool classification system containing six pool categories (lateral scour, fluvial, plunge, underflow, deflector and dam) based on flow and debris interaction (see figure 2.3). Other studies have shown that a considerable proportion of the vertical fall of channels can occur at the sites of debris jams, accounting for a 4% of the vertical drop along a 412m reach of channel in Vermont (Thompson, 1995) and 60% of the total drop in Little Lost

Man Creek in Northern California (Keller & Tally, 1979). Debris jams, therefore, may act as local base levels and sediment storage zones which provide a buffer in the sediment routing system (Heede, 1985, Bilby, 1981).

Thompson (1995) found that LWD causes an important negative feedback mechanism where, in the case of channel degradation, there is an increase in debris input due to mass bank failure, which in turn causes greater sediment storage. Increased sediment storage causes channel bed elevation to rise, tending to reduce bank heights and the rate of bank failure and debris input is, therefore reduced. On this basis, Klein et al. (1987) argue that jam removal can reduce the base level for the channel upstream and may trigger bank erosion. However, in an experimental study by Smith et al. (1993a and b) it was found that, while the removal of debris from a small gravel bed stream initially caused a four-fold increase in bed load transport at bankfull flow, the associated loss of scour turbulence and greater flow resistance imparted by alternate bars actually resulted in a reduction in stream power which was compensated for by sediment deposition and net channel aggredation.

Potential energy is dissipated at jams and jam energy loss may be as much as 6% of total potential energy (MacDonald et al., 1982). Shields & Smith (1992) found that the Darcy-Weisbach friction factor was 400 % higher at base flow in an uncleared river reach compared to a cleared condition, but that this value declined to 35% at high flows. The velocity distribution is also far more heterogeneous in debris-filled reaches, especially at low flow. Changes of stream power distribution due to flow resistance effects in turn give jams the ability to influence the location of erosional and depositional processes. Also, the backwater effect created by jam back-pools may induce local silting (Keller et al. 1976). Thus, in small, stable channels log steps generally increase bank stability and reduce sediment transport rates by creating falls, runs and hydraulic jumps.

Figure 2.2 shows how potential energy is lost through a log-step sequence, as outlined by Marston (1982). The localised dissipation of energy can, however, result in associated local scour and bank erosion which causes channel widening. Bank failure may also occur through flow diversion around a debris obstruction (Murgatroyd & Ternan, 1983). Davis & Gregory (1994) have also suggested a mechanism whereby bank failure is induced through the erosion of a porous, gravel, bank subsurface due to the greater hydrostatic pressure caused by debris-dammed flow. Conversely, Keller & Tally (1979) have observed that flow convergence under logs may cause channel narrowing, with sediment storage upstream and a scour-pool downstream of the log step.

As drainage area increases and the channel width/tree size ratio exceeds unity, flow is diverted laterally, to induce bank erosion through local basal scour. Hogan (1987) found that, in undisturbed channels in British Columbia, organic debris orientated diagonally across the channel resulted in high width and depth variability. However, in catchments where there had been logging operations the majority of in-channel discarded timber was orientated parallel to the flow and it subsequently became incorporated into the stream banks, protecting them from erosion. Nakamura & Swanson (1993) and Keller & Swanson (1979) have suggested that there is a wide range of types of interaction between debris jam and channel processes, progressing from local base level control and possible local widening in low-order streams, to lateral channel shifts and even meander cut-off in middle-order channels, where debris is moved into larger more coherent jams which may either increase or decrease the channel stability depending upon the erodibility of bed and banks. In larger channels still, bars may form and flow bifurcate around debris obstructions This last process has been documented by Nanson (1981) in British Columbia, who found that organic debris deposited at low flow provided the nuclei for development of scroll bars, through the local reduction of stream power. Hickin (1984) also observed crib-like bar-head features, but was undecided regarding whether the debris caused bar formation, or whether the bars pre-dated and trapped the debris. In either case, organic debris would, at the very least, enhance sediment deposition and bar formation.

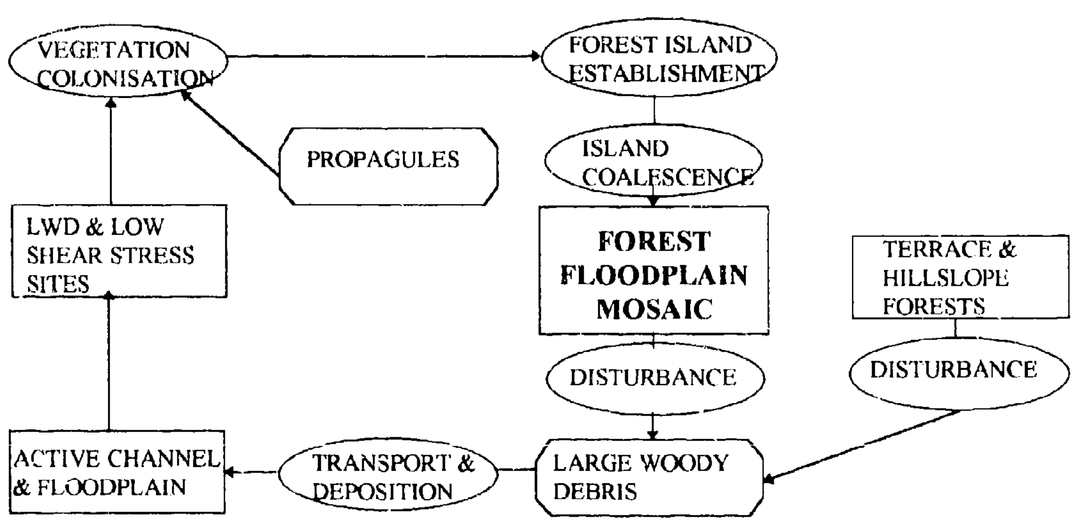
2.4 ECOLOGICAL IMPACT OF LWD

LWD dams are very important in small stream ecosystems because they provide a source of organic matter and retain floating leaves and twigs in the dam structure and backwater pools. This coarse particulate organic matter (CPOM) is broken down by shredder invertebrates in the low energy pool environment, creating fine particulate organic matter (FPOM) and dissolved organic matter (DOM), which are the required energy sources of a succession of invertebrate species who are, in turn, the energy source of high fauna species. Bilby & Likens (1980) found that the percentage of the standing stock of organic matter retained by jams changed from 75% in first-order, to 58% in second-order, and 20% in third-order streams because the prevalence of dam type jams declined downstream. The volume of CPOM therefore declines downstream, while the volume of FPOM and DOM increases. This gives rise to a spatially varied invertebrate community, changing from shredders in small channels to gathers of FPOM downstream. Smock et al. (1989) and Wallance & Benke (1984) found similar correlations between debris volume and invertebrate abundance in sand-bed streams,

where debris provides the only stable substrate for organic matter retention and invertebrate habitat. Higher species, such as fish, use debris and associated pools for shade, protection from predators, feeding and spawning grounds. The pools and falls created by log steps also help to oxygenate the flow, and provide a variety of different energy environments which are can be colonised by niche species.

In addition to providing essential fauna habitat, LWD is also a vital factor in the development of the riparian forest mosaic (Fetherston et al., 1995). Debris deposition in the channel and on the floodplain creates sites of low boundary shear-stress where vegetation colonisation can take place. This leads to the development of vegetation-stabilised islands and bars (affecting the geomorphological development of the channel) which may subsequently coalesce and/or become attached to the bankline to form new areas of forested floodplain that provide shade, bank stability and supply and storage of organic matter, sediment, water and new LWD. Figure 2.4 shows a modified version of the LWD-driven model of Fetherston et al., (1995) for riparian forest development, based upon research findings from the Pacific Northwest.

Figure 2.4 Conceptual model of montane riparian forest development. (Modified from Fetherston et al., 1995)



2.5 MANAGEMENT STRATEGIES

Until basic research concerning in-channel LWD began to suggest otherwise, it was commonly believed that LWD was detrimental to the fluvial system, hydraulically, ecologically and geomorphically. On this basis, reasons for debris removal included:

a) To improve navigation;

b) To increase channel conveyance by reducing roughness;

c) To eliminate bank erosion;

d) To facilitate the migration of fish, especially salmon (MacDonald, 1982).

It is now recognised that there are advantages to be gained by maintaining or even increasing in-channel debris accumulations (Gregory & Davis, 1992; Keller & McDonald, 1995). Management strategies that are currently advocated vary widely, however. This perhaps reflects our, as yet, incomplete understanding of LWD dynamics in different channel environments, and because goals vary between different management strategies. In this respect effective debris management depends on the underlying aims of the proposed management action.

Successful management also depends upon a comprehensive understanding of the following hydrogeomorphological factors (Gregory & Davis, 1992):

a) The relationship between river channel processes and river channel morphology;

b) Awareness of the timescales over which river channels may adjust;

c) Consideration of channel management in the wider context of river basin management.

More specifically, debris management must consider:

a) Channel stream power characteristics;

b) Sediment movement and storage relationships (high/low; fine/coarse sediment; suspended/bedload);

c) Channel stability;

d) Size and character of river channel in relation to debris size;

e) Spacing and frequency of jams;

f) Size and character of jams, and orientations of component material;

7) Age and stability of component materials.

In an evaluation of soft engineering for in-stream structures, including some using woody debris, to mitigate the effects of highway construction in British Columbia, Miles (1995) found that nearly 50% of the structures had been severely damaged after 8 to 14 years. Miles

attributed this problem to insufficient understanding and consideration of the stability of the structures in a high energy river environment. He concluded that soft restoration techniques may not be appropriate in highly energetic mountain rivers and that, if restoration is to be performed, funding must be made available for long term monitoring and maintenance.

There appears, in general, to be a consensus of opinion amongst researchers interested in LWD regarding appropriate management approaches for channel restoration. Bren (1993) and Nunnally (1978) argued that the riparian zone should be left undisturbed, in a natural state (although defining natural is difficult in most channels) and that, because debris is so important for the river ecosystem, debris jams should be left in place. Keller and McDonald (1995) studied catchments which had been disturbed by logging operations. They recommended that a riparian buffer strip should be left to maintain the natural LWD supply and warned that landsliding events caused by badly controlled logging operations, can cause excessive LWD input which is detrimental to stream habitat and flow and sediment conveyance.

There may be a case in streams lacking a wooded riparian strip for the introduction of debris jams (Keller & McDonald, 1995). If a debris recharge policy is to be implemented, however, it is important that debris jam volume and orientation emulates the values which would be found under natural conditions (Robinson & Beschta, 1990). Wallace & Benke (1984) concluded that, in most instances, the best management is probably no management, except where adjacent floodplains have to be protected from flooding.

Comprehensive studies of coarse woody debris in relation to river channel management have been carried out by Gregory and Davis (1992) and Gurnell and Gregory (1995a and b). The collation of analyses from twenty two research papers with primary field studies carried out in the New Forest, UK (Gregory & Davis, 1992) demonstrated the significance of LWD to channel morphology, processes and ecology (Figure 2.5) and produced a preliminary table of debris management criteria based upon their findings (Figure 2.6). They conclude that, "... a conservative approach to debris removal should be adopted for most areas, but that different strategies are needed according to the characteristics of particular localities." (Gregory and Davis, 1992, pg. 133).

It should be noted, however, that this study, in common with most others cited, was carried out in an essentially stable, equilibrium channel environment where changes to channel morphology are negligible and significant impacts relate mostly to ecological habitat diversity.

Also, little attention is paid to "different strategies" that may be required in contrasting channel environments and there is no discussion of conflicts between practices advocated by various

organisations in the USA. For example, Gregory & Davis (1992) suggest that, based on their literature survey, no debris should be removed from channels exhibiting low stability (Figure 2.7). However, this contradicts the practice described by Brookes (1985, pg. 64), "In North America the concept of channel restoration was developed in North Carolina under the funding of the Water Resources Research Institute of the State University ...Restoration is achieved by removing debris jams and providing uniform channel cross-sections and gradients whilst preserving meanders, leaving as many trees as possible along the stream banks, and stabilising banks with vegetation and rip-rap where necessary ...".

Similar approaches have been documented and carried out by numerous researchers and organisations in the USA including: McConnel et al. (1980), based upon work on the Wolf River, Tennessee; the American Fisheries Society (1983), in a publication entitled "Stream Obstruction Removal Guidelines", (see Figure 2.8); Shields and Nunnally (1984); and, Palmiter (Institute of Environmental Sciences, 1982).

The recommendations of Palmiter (1982) include the following:

a) Removal of log-jam material by cutting it to a manageable size;

b) Protection of eroding banks using brush piles and log-jam material, with rope and wire;

c) Removal of sand and gravel using brush-pile deflectors;

d) Revegetation to stabilise banks and shade-out aquatic plants;

e) Removal of potential obstructions such as trees and branches;

Willeke & Baldwin (1984) assessed the Palmiter techniques and found them suitable for areas experiencing chronic, low intensity flooding and bank erosion, but not advisable for rivers with extreme flood problems. They are also found to be largely ineffective for erosion control where the mechanism of bank failure is that of mass wasting rather than tractive force erosion (Hasselwander, 1989).

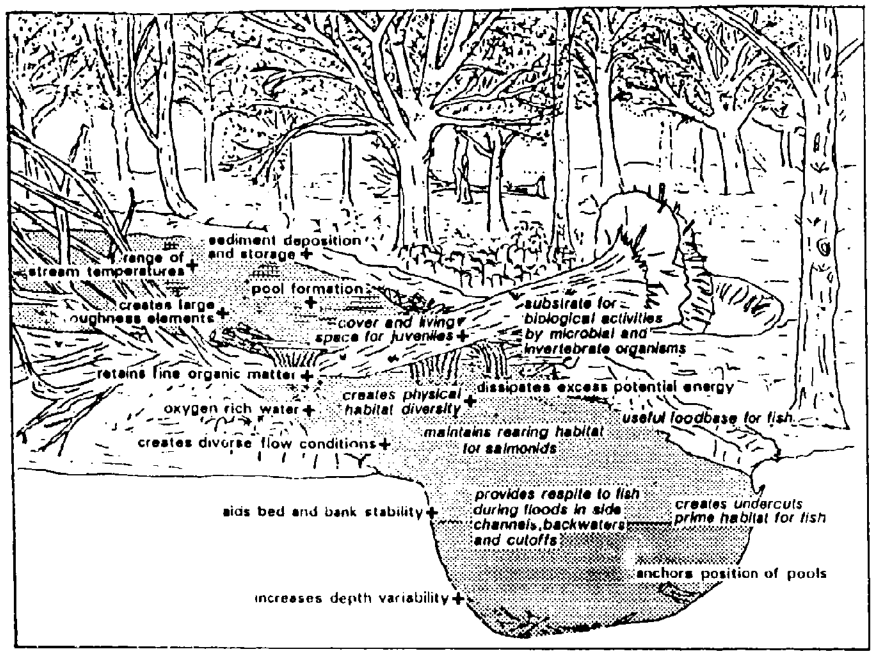
It is evident from the preceding discussion of LWD management strategies that recommendations vary considerably ranging from limited or no interference to total clearance of debris from the channel. These apparently contradictory recommendations must be viewed in the light of the overall management program that they were designed for, as requirements for habitat enhancement differ from those for flood defence.

Finally, and of great importance, is the fact that the recommendations of type made by Palmiter and others, address debris management predominantly in, low gradient, sand-bed, and perhaps unstable, flood prone rivers (South east USA), while those prescribed by Gregory and

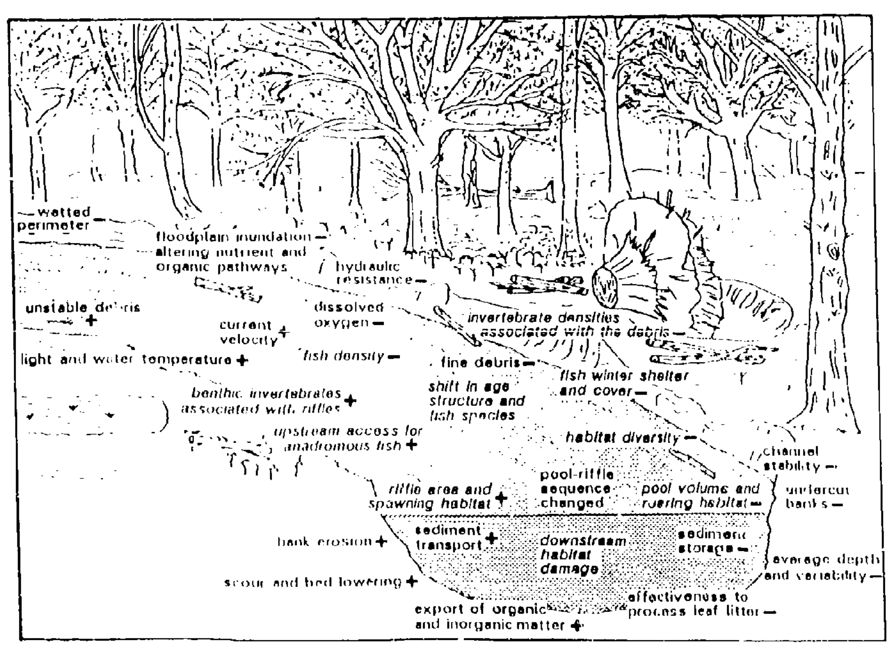
Davis (1992) and others are based upon findings from upland, even montain, gravel-bed rivers and streams (Pacific Northwest USA). Process relationships between the debris and the channel are likely to differ between these two fluvial environments, although, as yet, these differences have not been recognised or investigated. Indeed, while there is a wealth of research concerning the geomorphological impacts of LWD in upland gravel-bed rivers, there has been little comparable research in lowland, sand-bed, and/or unstable river environments.

Figure 2.5 The significance of coarse woody debris dams for channel morphology, channel processes and ecology (modified from Gregory and Davis, 1992)

DAM PRESENT



DAM REMOVED



Characteristics which relate to ecological habitats are shown in italics

Reproduced by permission of John Wiley & Sons Ltd., after Gregory & Davis, 1992

Figure 2.6 Determinants for a management strategy for rivers in woodland areas (modified from Gregory and Davis, 1992)

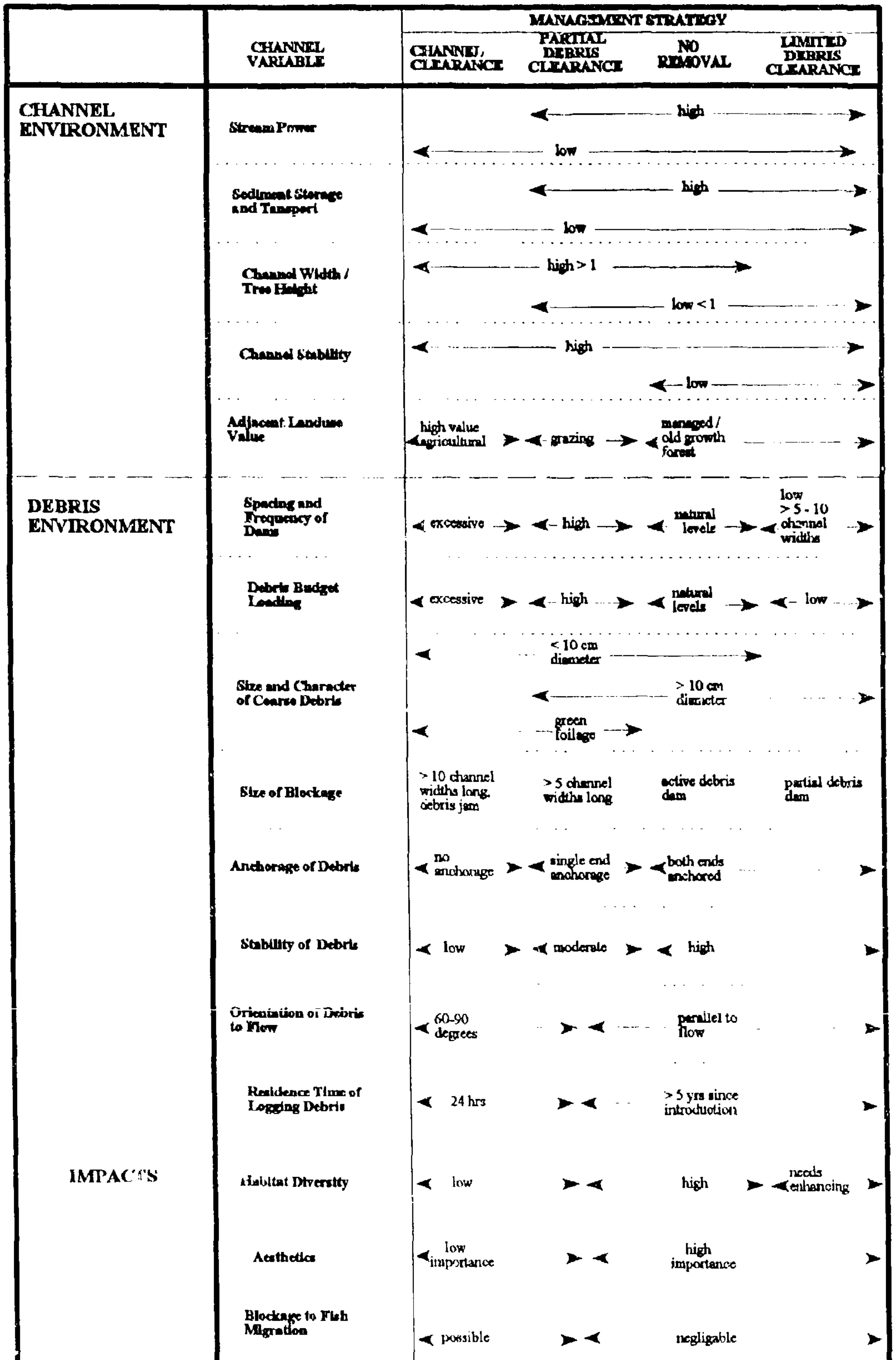


Figure 2.7 Definition of Stream Obstruction Conditions (Modified from American Fisheries Society, 1983)

Condition One These stream segments have acceptable flow and no work would be required. They may contain various amounts of instream debris and fine sediment, such as silt, sand, gravel, rubble, boulders, logs and brush. In certain situations flow may be impeded, but due to stream and land classification or adjacent land use, this is not a problem	**Management Criteria** No work to be conducted.
Condition Two These stream segments currently have no major flow impediments, but existing conditions are such that obstructions are likely to form in the near future, causing unacceptable problems. This condition is generally characterised by small accumulations of logs and/or other debris which occasionally span the entire stream width. Accumulations are isolated, not massive and do not presently cause upstream ponding damage.	**Management Criteria** Equipment that will cause the least damage to the environment shall be selected for performing the work. First consideration will be given to the use of hand operated equipment such as axes, chain saws, and winches to remove accumulations. Boats with motors may be used where needed. When the use of hand operated tools is not feasible, heavier equipment may be used, e.g. small tractors, backhoes, bulldozers, log skidders and low PSI equipment. Equipment shall be operated in a manner that results in least damage to vegetation and soils of the project area. In some cases explosives may be used resulting in less damage. Debris designated for removal from the stream or floodway should be removed or secured in such a manner as to restrict its re-entry into the channel. Generally, it should be positioned so as to reduce flood flow impediment
Condition Three These stream segments have unacceptable flow problems. Obstructions are generally characterised by large accumulations of lodged trees, root wads, and/or other debris that frequently span the entire stream width. Although impeded, some flow moves through the obstruction. Large amounts of sediment have not covered or lodged in the obstruction	**Management Criteria** Equipment limitations will be the same as for condition two segments. Work shall be accomplished within the channel or from one side of the channel where possible. Selective tree clearing shall be limited to the minimum necessary for equipment access and efficient operation of equipment on the worked side of the channel. Disposal of equipment may be accomplished by removing it from the floodplain or by burning, burying or piling, as appropriate, with the minimum amount of disturbance to vegetation. Piled debris shall be gapped at frequent intervals and at all tributaries and distributaries.
Condition Four These stream segments are characterised by major blockages causing unacceptable flow problems. Obstructions consist of compacted debris and/or debris that severely restricts flow	**Management Criteria** Blockage removal may employ any equipment necessary to accomplish the work in the least damaging manner. Work should be accomplished from one side of the channel where practical. Material shall be disposed in accordance with guidelines presented above for condition three segments. Spoil piles should be constructed as high as sediment properties allow. The placement of spoil around the base of mature trees should be avoided.
Condition Five These stream segments posses unique, sensitive, or especially valuable biotic resources and should be dealt with on a case-by-case basis. Examples include, but are not limited to: Areas harbouring rare or endangered species, shellfish beds, fish spawning and rearing areas, and rookeries.	**Management Criteria** Special provision for protecting unique, sensitive, or productive biotic resources shall be developed by appropriate professionals on a case by case basis.

3 REGIONAL CHARACTERISTICS

3.1 Introduction

Creeks in northern Mississippi have received considerable attention from geomorphologists and engineers recently in an effort to try and stabilise channels which have been degrading through knickpoint migration due to lowering of the base level (Schumm, 1984). Degradation problems have been combated by the construction of grade-control structures which reduce stream power by means of a hydraulic jump. Degradation has been caused in the past forty years by several factors including trunk stream dredging, changes in farming practices and channel straightening which was originally carried out to reduce flooding and improve drainage of valley bottom lands. The degradation problem is manifest mainly in the bluffline hills, away from the Mississippi delta and floodplain, where creeks are often ephemeral and "flashy" in nature, but flow through highly erodible alluvium and loess.

The study sites chosen all lie on this type of material, in the Bluff-Line Hills. Plate 3.2 shows a geological map of Mississippi and the location of the DEC study area.

3.2 GEOLOGY

3.2.1 Pleistocene-Holocene Stratigraphy

Four major stratigraphic units make up the Pleistocene-Holocene valley fill in northern Mississippi. From oldest to youngest, these are:

1) Meander Belt 1 (MB1) :

A fine-grained deposit which contains five types of sediment: point bar, channel, natural levee, abandoned channel, and backswamp. If natural levee and abandoned channel-fill sediments crop out in the toe slope they provide a measure of stability, whereas point bar, channel, and backswamp sediments are highly erodible. The level of channel degradation has now progressed to the point where toe-slope materials are comprised of these units.

2) Lacustrine (Old Palaeosol) (L) :

Deposited in a low energy fluvial environment, these sediments are homogeneous and comprise loess and alluvially re-worked loess. Characteristic of this unit is a well-developed polygonal structure, with seams up to 2 cm thick, filled with unconsolidated material. These seams present distinct planes of weakness in the material. The unit also contains iron concretions in the lower level which offer some resistance to knick-point migration (Little et al., 1982). In this study Old Palaeosol outcrops were recognised in both Lick Creek and Nolehoe Creek.

3) Meanderbelt 2 (Young Palaeosol) (MB2) :

These materials are fine-grained, weathered, less cohesive, and, therefore, more erodible than Meanderbelt 1. These sediments form the upper portion of many banks and represent a significant source of suspended and bedload sediments. This layer is highly permeable compared to the Old Palaeosol, and piping often occurs at the L/MB2 interface. Piping is an important contributor to bank failure (Grissinger, 1982).

4) Post Settlement Alluvium (PSA) :

PSA was deposited during the last 150 years due to the rapid vertical accretion of floodplain sediments following European settlement of the region. Up to 16 ft of deposition has occurred due to farming malpractice that commenced in the 1830s and continued until the 1930s. The bulk of sediment has been deposited in the upper and middle reaches of valleys. These sediments are unweathered and cohesionless and provide a principle source of suspended sediments. This Pleistocene-Holocene stratigraphy is shown in as a column in Figure 3.1a and in cross-section in Figure 3.1b.

3.3 GEOMORPHOLOGY OF CHANNELS IN NORTHERN MISSISSIPPI

3.3.1 Bank Characteristics

In all four creeks studied, the Pleistocene-Holocene MB1, L and MB2 units are located within the channel banks to a depth of 4-8 feet. This loess material is fairly uniform in color, and composed of a brown-gray-sandy silt to silty clay (Schumm et al.,1984). The chief characteristics of this loess are:

a) uniformity of texture;

b) Irregularity of shape and extreme fineness of particles;

c) Generally massive structure;

d) Lack of coherence;

e) Capacity to stand as vertical-faced walls;

f) Capacity to absorb water.

3.3.2 Bed and Bank Failure Mechanisms in Degrading Channels

Knick zones can be observed in nearly all drainage basins in northern Mississippi. These features reflect an abrupt change in channel gradient, the typical knick-point unit being characterised by a 2-4 ft vertical fall within a cohesive unit, which reflects an overall incision of

the channel in response to regional lowering of the base level (Schumm et al., 1984). Perched tributaries, drainage ditches which enter the main stream at a higher elevation than the bed of the main channel and mature tree growth significantly higher than the channel bed are also characteristic of overall incision. The bed of the middle to upper portion of Byhalia Creek, for example, is dominated by knick zones, perched tributaries and undercut structures.

The principal units being degraded in northern Mississippi are Meanderbelt 1 and Lacustrine. However, natural levee and abandoned channel sediments of MB1 are more resistant to erosion than channel, point bar and backswamp sediments and offer some resistance to knickpoint migration. Upstream knickpoint migration is a function of flood frequency and bed material erodibility. Where a knickpoint has been at the same location over a period of time, a characteristic widening of the channel, downstream, takes place. This is known locally as a "blow-out" (Begin et al., 1981).

A sequence of channel reach types associated with knickpoint migration in northern Mississippi has been conceptualised by Schumm et al. (1984), in what has been termed the Channel Evolution Mode (CEM). This idealised sequence is shown schematically in figure 3.1c. Along a given channel morphological classification Types 1 through 5 occur in sequence downstream and, at a given location, will alsooccur, in series, over time. The data used to determine the channel evolution model were obtained from Oaklimiter Creek, and are presented in table 3.1. The morphological categories, as described by Watson et al. (1993) are outlined below.

- *Type 1*: These reaches are in equilibrium and are characterised by a sediment transport capacity that exceeds sediment supply, a bank height that is less than the critical height, a saucer shaped cross-section, possibly small precursor knickpoints and a channel bed with little or no sediment deposited. Width to depth ratios are highly variable.
- *Type 2* : These reaches are located immediately downstream of primary knickpoints and are characterised by sediment capacity that exceeds sediment supply, a bank height that is equal to the critical bank height, rectangular cross-section, a channel bed with little or no sediment deposited, a lower bed slope than Type 1 reaches because degradation reduces bed slope and a lower width-depth ration value than Type 1 reaches because the depth has increased but the banks are not failing.
- *Type 3* : These are located downstream of Type 2 reaches and are characterised by a sediment transport capacity that is highly variable with respect to sediment supply, a bank height that is greater than the critical height and erosion due primarily to slab type failure, an

accumulation of less than two feet of sediment in the bed channel which locally can be much higher if there have been recent bank failures that have not been removed by subsequent flows, a channel depth that is somewhat less than that in the Type 2 reaches due to limited aggradation and channel widening due to bank erosion.

- *Type 4* : These are located downstream of Type 3 reaches and are characterised by a sediment supply that exceeds transport capacity cause aggradation of the channel bed, the formation of longitudinal berms along the channel margins which eventually define the edge of the effective discharge channel and the elevation of a new floodplain within the incised channel, a bank height approaching critical with failure rate lower than in Type 3 reaches which is enhanced by berms loading the bank toe, a near trapezoidal cross-sectional form, and width-depth ratio values that are higher than those for Type 3 reaches because aggradation has reduced the channel depth and bank failure has increased the width of the channel.
- *Type 5* : These are located downstream of Type 4 reaches and are characterised by a near equilibrium between sediment transport capacity and sediment supply for the channel cross-section that is defined by the top of the berms, a bank height less than critical and reduced bank angles due to incorporation of failed bank material into berms, colonisation of berms by riparian vegetation which increases hydraulic roughness and thus promotes further accretion, sediment depth in the bed of the channel that generally exceeds four feet, a compound channel with the low stage defined by the tops of the berms and high stage defined by pre-incision floodplain, and width to depth ratios that are higher than those of Type 4 reaches. Type 5 reaches define the new dynamic equilibrium conditions in the channel.

This model assumes that the channel is responding to a single base level lowering event and that the channel perimeter is readily adjustable both vertically and laterally. The model is also only applicable at a system wide level as local processes such as meander bend erosion will distort the sequence. Never-the-less, the sequence provides a framework whereby the complex adjustments in a channel can be understood and the morphology of individual reaches related to processes operating both upstream and downstream in the network.

Bank erosion in Type 3 and 4 channels can cause considerable problems in terms of loss of agricultural land, and the undermining of bridges and other structures. Sediment production through bed erosion and bank failure from the adjusting channel segments also causes problems further downstream, where reservoirs can become choked, navigation channels blocked and the risk of overbank flooding exacerbated.

Figure 3.1a Generalised Stratigraphic Section of Pleistocene-Holocene Valley Fill, Northern Mississippi (modified from Schumm, 1984)

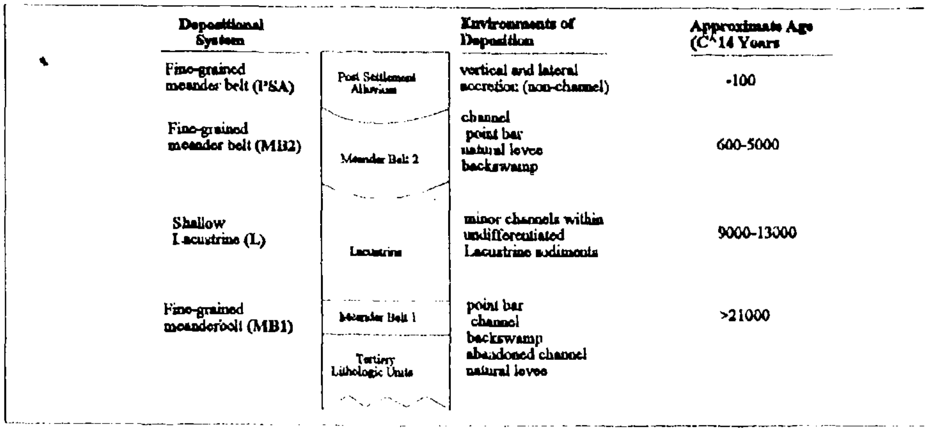


Figure 3.1b Schematic Longitudinal Profile of the Northern Mississippi Valleys Showing the distribution of Pleistocene-Holocene Stratigraphic units (modified from Schumm, 1984)

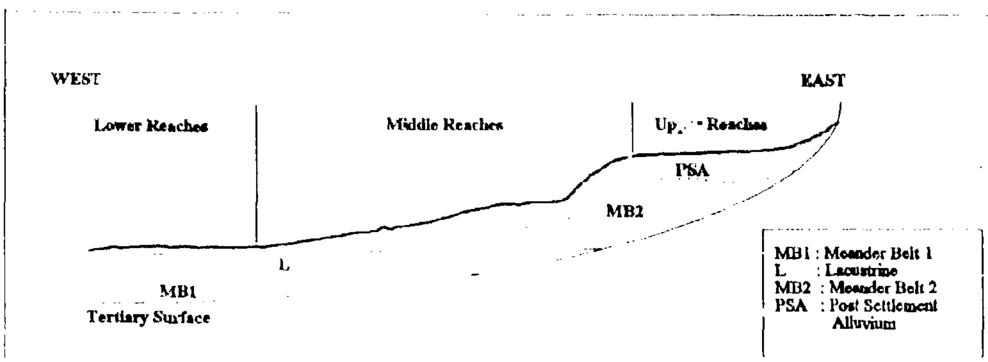
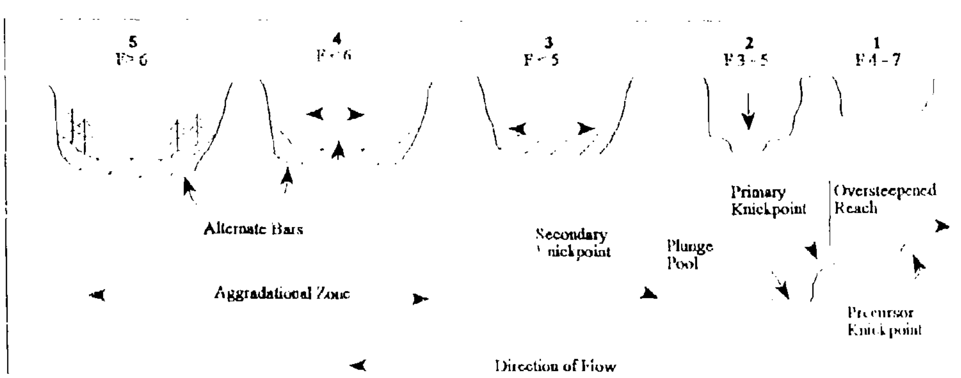


Figure 3.1c Schematic Longitudinal Profile of an Active Channel Showing Identifiable Features (modified from Schumm, 1984)



Schematic cross section profiles corresponding to reaches on the longitudinal profile show the evolution of the reaches from Type 1 to Type 5. Typical width-depth (F) values are shown. Size of the arrows indicate the relative importance and direction of the dominant processes, degradation, aggradation and lateral bank erosion.

Figure 3.2 Geological map of Mississippi showing the DEC survey area (modified from Watson et al., 1993)

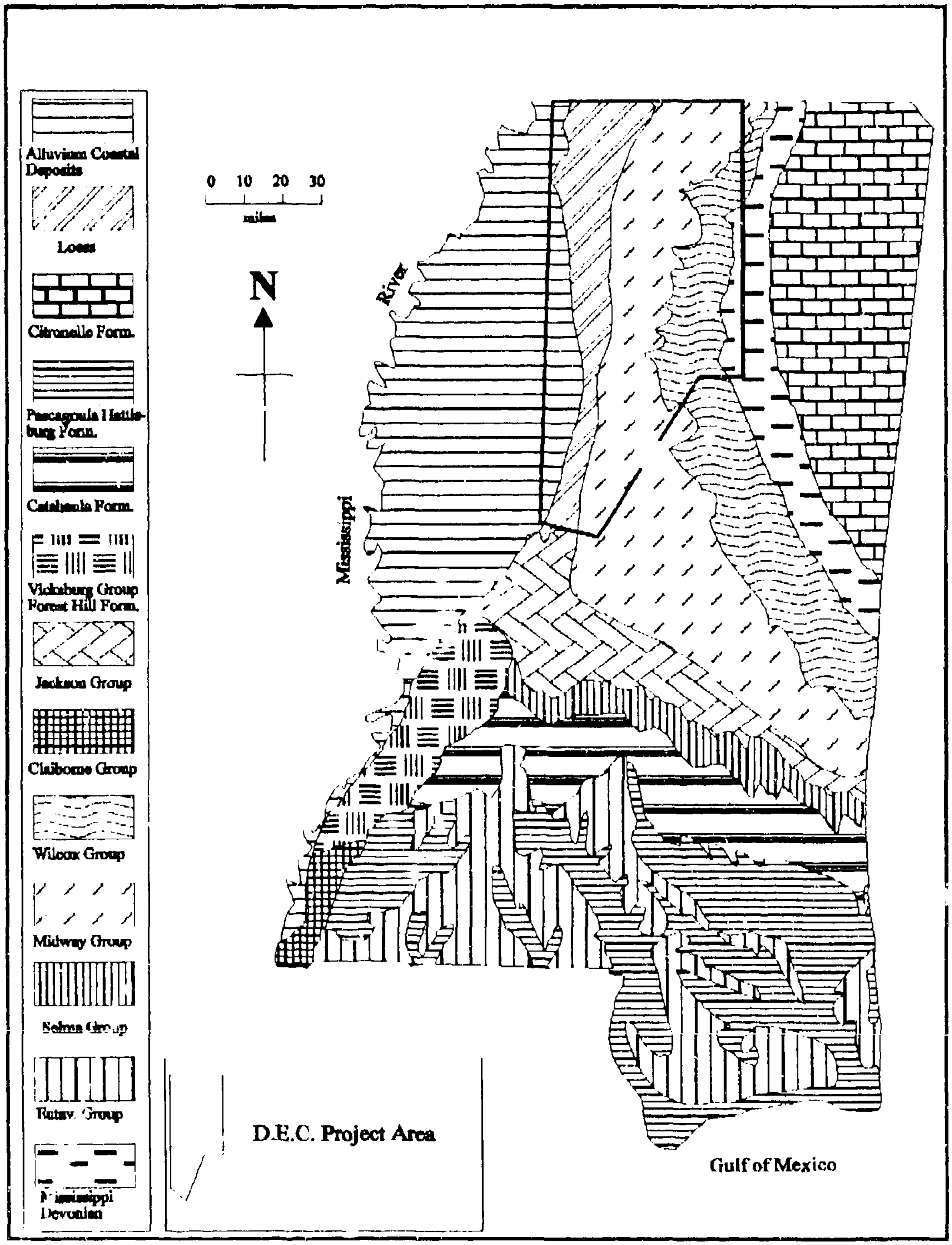


Table 3.1 Summary of morphometric data used to determine channel evolution model - Oaklimiter Creek (after Schumm et al., 1984)

Stage	Location	Top Width (ft)	Depth (ft)	Width/ Depth Ratio (ft)	Thalweg Slope (ft/ft)	Depth of Sediment (ft)	Dominant Process
I	upstream of headcut	82	17.3	4.7	0.0020	0	transport of sediment
II	Immediately downstream of headcut	82	21.6	3.8	0.0018	variable 0-2	degradation
III	Downstream of II	100	20.1	4.9	0.0018	1.5	rapid widening
IV	Downstream of III	115	19.2	6.0	0.0016	2.5	aggradation and devt. of meandering thalweg
V	Downstream of IV	119	15.3	7.8	0.0010	6.3	aggradation and stabilisation of alternate bars

Riverbank retreat in type 3 and 4 reaches takes place by fluvial erosion and bank mass instability (Thorne, 1981). The relative amount of vertical and lateral erosion (which cause an increase in bank height and bank angle, respectively) is, therefore, a function of bank material micro-scale electrochemical properties (in cohesive material) bank geometry, bed materials and excess flow boundary shear-stress above a critical value for entrainment. Mass instability on the other hand, depends on macro-scale soil properties and bank geometry. Poor drainage and consequent saturation promotes bank failure by causing positive pore-water pressure which, in turn, reduces effective cohesion and, therefore, the factor of safety (Fs = restraining/disturbing force). The most favorable conditions for poor drainage are heavy precipitation and/or rapid channel flow draw-down, which changes the bank from submerged to saturated conditions effectively doubling the bulk weight of bank material (Thorne, 1978). Slab-type failure is most common in steep banks (>60 degrees, Taylor,1948), where a block shears along a planar surface and topples forward into the channel. This mechanism is promoted by the development of tension cracks within the bank. The removal of woody perennial vegetation from the top of banks enhances the formation of these cracks although large vegetation, such as trees, may act to hasten failure by surcharging (adding excess load to) the bank if the root network is undercut.

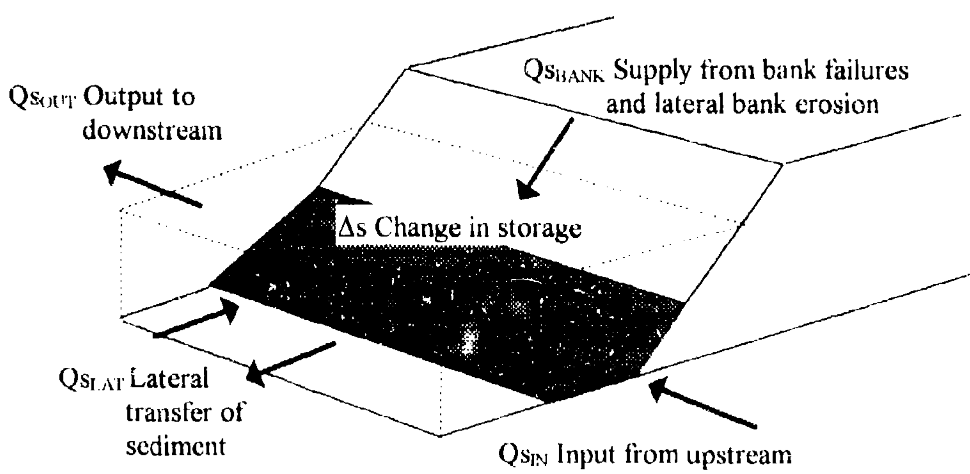
Downstream of a knickpoint the channel widens by mass failure, followed by basal clean-out of slump debris, until stream power has fallen to a level where failed bank material can no longer be carried away. A sinuous channel then develops, within the confines of the incised and blown-out terrace walls of the incised canyon. Where a meander encounters the terrace wall, bank failure may continue to take place, probably by a rotational slip of the lower angle, higher

bank. The channel eventually becomes stable once more, except that it lies within an entrenchment in the former floodplain.

While bank failure is related to bulk mechanical properties, the rate of retreat is dependent upon the fluvial entrainment of failed bank material. This phenomenon has been termed Basal Endpoint Control (Thorne, 1978), and it explains how the rate of channel width adjustment is controlled by the balance of sediment moving into and out of the basal area.

Initially, slumped debris protects the bank from further erosion and failure through buttressing, bank toe loading, and by buffering fluvial activity away from the bank base. Eventually debris is removed however, (it is much less resistant to erosion than the intact bank) and further basal erosion of the bank takes place. Figure 3.3 shows a schematic diagram of sediment fluxes in the near bank zone.

Figure 3.3 Basal Endpoint Control : Sediment flux in the near bank zone (modified from Darby & Thorne, 1993)



There are three states of basal endpoint control, and therefore lateral channel stability :

1) INPUT > OUTPUT (Impeded removal):	Basal sediment wedge accretion, berm formation and increasing bank stability
2) INPUT = OUTPUT (Unimpeded removal):	Equilibrium between processes delivering and removing sediment, bank retreat limited.
3) INPUT < OUTPUT (Excess basal capacity):	Removal of sediment wedge by basal scour causing basal lowering, a reduction

in bank stability, and an increased bank retreat rate.

Channel evolution models such as that developed by Schumm et al. (1984) use the theory of Basal Endpoint Control to explain the sequence of degradation, widening and stabilisation that is characteristic of unstable Bluff Line streams.

Grissinger (1982) recognised that bed stability is also controlled by velocity-dependent hydraulic properties and describe how degradational erosion of the Lacustrine-Old Paleosol material is influenced by its polygonal structure and is initiated through the development of a narrow chute, which widens and deepens, with discrete blocks being eroded and entrained.

It is channel bank failure downstream of a knickpoint in wooded areas that leads to the input to the channel of large quantities of trees and other organic debris. The size, orientation, and persistence of organic debris then affects stream power, flow routing, the Basal Endpoint Control state and bank erosion rates. It is, therefore, probable that the processes and morphology in the idealised sequence of the Channel Evolution Model will be distorted by the input of substantial quantities of LWD in Type 2 and 3 reaches if the riparian zone is heaviliy wooded. Debris jams may either act to reduce local channel instability, through energy dissipation and sediment retention, or may assist in driving bed and bank erosion by causing local bed scour and flow diversion into channel banks. It may, therefore, be necessary to refine the channel evolution model to describe adequately the form-process relationships occurring in unstable channels with wooded riparian zones. The affect of LWD on the Channel Evolution Model is an interesting topic and one which is addressed in the results analysis of this report

4 RESEARCH METHODS

Field ata collection was undertaken in May 1995 and August 1996. Debris jams were surveyed with long-profiles and cross-sections taken at 23 reaches which are monitored by the U.S. Army Corps of Engineers as part of the DEC monitoring research program. A full description of the DEC monitoring site characteristics is given in Watson et al. (1993). The reaches surveyed were between 1220 and 3660 metres long and ranged in upstream watershed area from 9 to 388 Figure 4.2 shows the rivers and major catchments of the project area in detail.

Reacheswere surveyed on the following creeks:

Nolehoe Creek	Sarter Creek	Lick Creek
Burney Branch	James Wolf Creek	Long Creek
Sykes Creek	Hotopha Creek	Fannegusha Creek
Worsham Creek (East)	Worsham Creek (Middle)	Worsham Creek (West)
Abiaca Creek	Harland Creek	Red Banks Creek
Otoucalofa Creek	Coila Creek	Lee Creek
Perry Creek	Hickahala Creek	Marcum Creek

These surveys provide a comprehensive data-set, which not only covers a range of drainage basin areas, from 9.5 to 256 Km^2, but also allows comparison of debris loadings between reaches with wooded and agricultural riparian zones, between straight and meandering reaches and between highly unstable and stabilising or equilibrium reaches.

Debris jam sites have been surveyed into the thalweg and cross-section data for each creek so that there position and associated changes in local channel geomorphology can be monitored over time. Data from the current survey has been processed, overlaid and compared with that collected in May 1994 so that an assessment can be made of the rate of debris input, the longevity of jams and, therefore, their effectiveness as geomorphological channel controls, and the changing patterns of associated sedimentation and erosion.

Debris jam sediment budgets have also been calculated to determine whether the net impact of debris jams is through sediment retention or sediment scour and mobilisation. Sedimentation processes are assessed using hydraulic geometry relationships. Volume of debris and number of jams, per unit reach length are also related to processes occurring in the sequence of stages in the Schumm channel evolution model (CEM).

Geomorphological reconnaissance was also performed at each jam site to document the volume of debris in each jam, to identify its mode of input into the channel, to determine the

jam type in terms of impact upon flow pattern and erosion, and to measure the volume of sediment retained in backwater areas or bars. The following variables were assessed at each jam site:

1) Debris jam volume: Estimated volume of woody material (m^3) in each jam. values are then summed for each survey reach.

2) Morphological classification: A debris classification system, modified from that developed by Robinson and Beschta (1989), which describes the geomorphological impact of debris jams throughout the drainage network. Figure 4.2 shows the original classification scheme and figure 5.2a shows the modified version. Jam classification types are as follows:

Underflow jams: In small catchments where fallen trees span the channel at bank-full level. Local bed scour may occur under debris at high flows, otherwise the in-channel geomorphic impact of the LWD is minimal.

Dam jams: In channels where the average tree height to channel width ratio is roughly equal to one, so that debris completely spans the channel cross-section. This type of jam causes significant local bank erosion and bed scour due to flow constriction and backwater effects will cause sediment deposition in the lower energy environment upstream. Bars may also form immediately downstream of the jam.

Deflector jams: Found where input debris does not quite span the channel so that flow is deflected against one or both banks causing localised bed scour and bank erosion. Subsequent bank failures result in the input of new LWD material to the reach, so that the jam builds up further. Backwater sediment wedges and downstream bars may form at this type of jam provided that stream power is dissipated by the jam to values below the critical level for bedload and suspended sediment transport.

Flow Parallel jams: Found where channel width is significantly greater than the key-debris length and flows are competent to rotate debris so that it lies parallel to the flow. Debris is also transported downstream in high flows and deposited against the bank-base on the outside of meander bends and at channel obstructions such as hydraulic structures. Related bank erosion and bed scour will be minimal, and bank toes may even be stabilised by debris build-up. Flow parallel debris may also initiate or accelerate the formation of mid-channel and lateral bars.

3) Blockage classification: Jams are classified, using the scheme developed by Gregory et al. (1985), according to their potential to block the downstream movement of water and sediment. The classification types are:

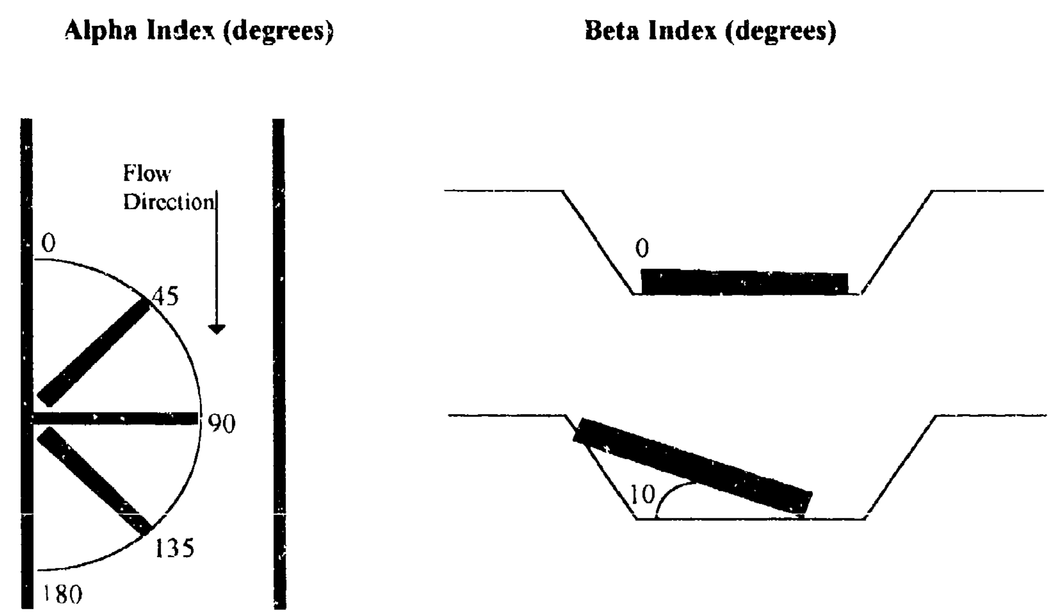
Active: Jam forms a complete barrier to water and sediment movement and also creates a distinct step or fall in the channel profile.

Complete: complete barrier to water/sediment movement, but no significant step.

Partial: Jam is only a partial barrier to flow.

4) Alpha/Beta Indices: The alpha angle describes the predominant alignment of the debris in the channel with respect to the flow direction. These indices were first used by Cherry and Beschta (1986) in connection with LWD flume experiments. The Beta angle is a measure of the predominant orientation of the debris jam material in the vertical plane, orthogonal to the flow direction. See figure 4.1 below.

Figure 4.1 Alpha and Beta Indices (modified from Cherry and Beschta, 1986)



5) Sinuosity: A visual estimate of channel sinuosity in the jam reach (straight, slightly sinuous, sinuous, meandering).

6) Knickzones: Presence of knickpoints or knickzones in the channel reach (a measure of channel instability).

7) Sediment: Bedload D_{50} classification (clay, silt, sand, gravel)

8) Deposition/Scour: Estimated volume of bar deposition, backwater sedimentation and bed/bank scour induced by each jam. Total deposition and scour values are then calculated for each channel reach.

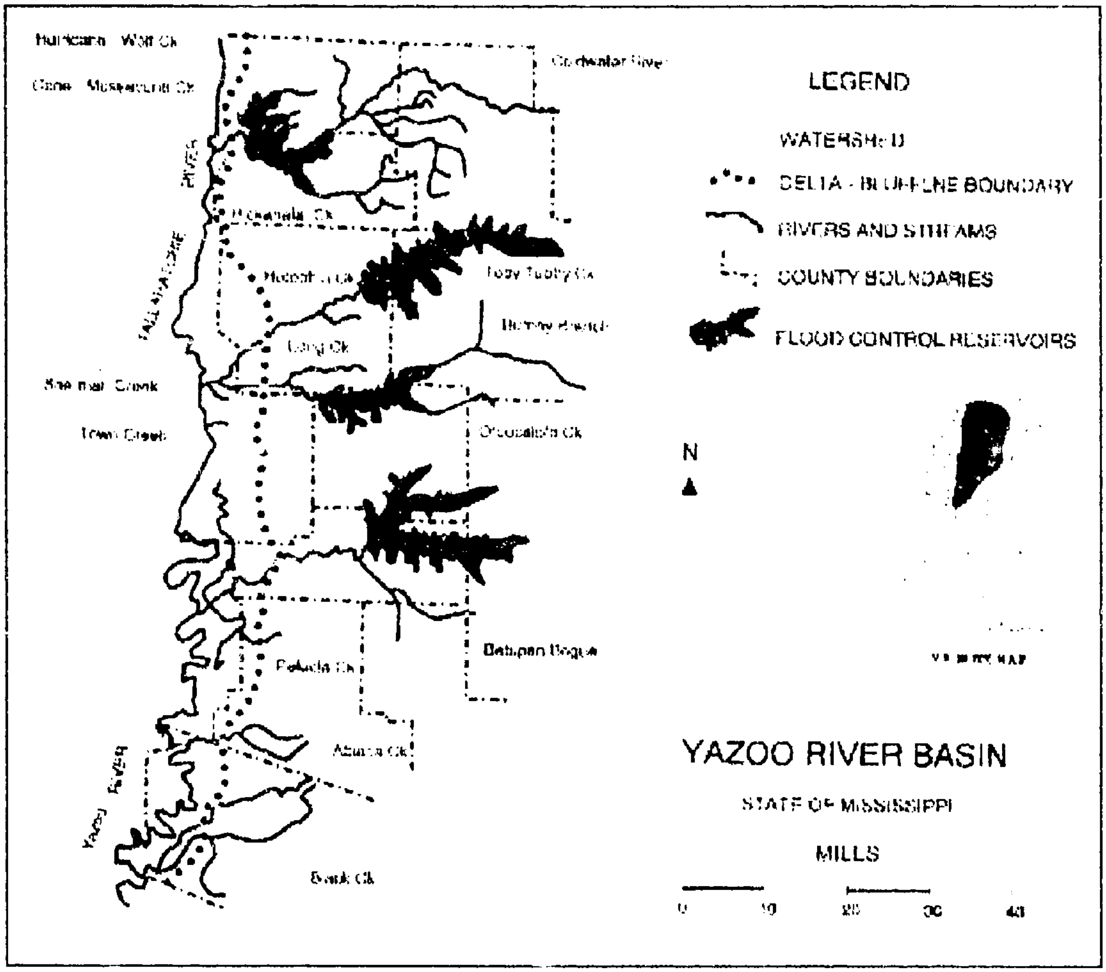
The debris volume and debris frequency measures, morphological classification, jam sedimentation and erosion, and net jam sediment budgets in each reach have been and plotted against three independent catchment variables. These are: upstream drainage basin area, reach-averaged channel width; and reach-average stream power per unit bed area. Stream power per unit bed areais calculated using the following equation:

$$\omega = \frac{\rho g Q s}{w} \qquad (3.1)$$

where, ω = stream power per unit channel channel length ($N/m/s^{-1}$), ρ= density of water (kg/m^3), g = gravitational constant ($9.81\ m/s^{-2}$), Q = predicted bankfull discharge (cumecs), s = bed slope (m/m), w = reach average channel width (m).

These independent catchment variables are used to determine whether the geomorphological effects of LWD have a coherent and predictable spatial relationship.

Figure 4.2 DEC project area site location map (modified from Cooper et al, 1996)



5 RESULTS AND DISCUSSION

All raw field data and calculations are listed in Appendix D.

5.1 Input Mechanisms

Debris jams were found in 17 of the 23 reaches surveyed. All reaches containing jams were found to have wooded riparian zones, while the 6 reaches with no significant debris accumulations were found to have non-wooded, open riparian zones.

'Key debris' (that is large trees which initiate jam formation (Nakamura and Swanson, 1993)) input mechanisms were found to fall into the following categories:

37% due to outer bank erosion in channel bends;

36% due to bank mass-wasting in degrading reaches;

12% due to wind-throw;

7% resulting from 'paleodebris' (material reintroduced into the channel from erosion of old alluvial deposits containing preserved debris);

5% initiated by large logs floated from upstream; and

4% were found to be formed by beaver dams.

Plate 1 shows debris input due to mass failure of the bank on Harland Creek and Plate 2 shows a beaver-LWD "dam" located on the sill of a low drop grade control structure on Worsham Creek.

If channels have wooded riparian zones, the largest volume of debris input can be predicted to occur where the channel is in phase two and three of the CEM or is actively meandering. Jams tend to form where the key debris elements fall into the river and, hence, are commonly located at bend apices or in unstable reaches downstream of knickpoints.

5.2 Distribution of LWD

Correlations were made between average volume of debris (per vol. Per 100m) measured in each reach surveyed against watershed area and stream power. Positive relationships were expected in these correlations, as found by Gregory et al. (1993), because debris is more likely to be mobilised and transported downstream into larger channels as flow competence increases. In fact, no statistically significant relationship was found between watershed area and debris volume. However, the relationship between stream power and debris volume was

found to be statistically significant using Pearson Product Moment correlation analysis, at the 0.05 confidence level. This relationship is shown in Figure 5.1a.

Correlations were made between average number of jams (jam frequency) per 100m reach length for each reach surveyed, watershed area and stream power. Negative relationships were expected in these plots because as channel size becomes greater flow competence increases and jams are, therefore, more likely to become dislodged (Swanson et al., 1984). However, neither correlation was found to have a statistically significant relationship.

The use of hydraulic geometry and energy relationships to predict the distribution of debris is, therefore, simple an approach to explain debris dynamics in these unstable channel environments. Reach stability, and channel sinuosity are probably better predictors of debris volume and the frequency of jams, because these factors to a large extent determine the rate of debris input.

Examination of the values for debris loadings for each Stage (1 to 5) of reach stability outlined in the Schumm's (1984) Channel Evolution Model were examined to determine whether loadings can be attributed to the processes occurring in the stages and, therefore, whether stage of evolution is a good measure of debris input rate. The CEM model is shown in Figure 3.1c.

It is expected that there would be very low debris input in stable, Stage 1 reaches, where mass failure of the bank is absent or limited. A rapid rise in debris input rate might be expected in Stage 2, reaches, where knickpoints are active, because although the channel has not yet begun to adjust laterally, large trees on the incised channel banks produce surcharging which could result in local bank failures. It is expected that there would be the highest debris input rates in Stage 3 reaches due to widespread mass failure of the banks following degradation. Finally, in Stage 4 reaches, where bank erosion rates decline and in Stage 5 reaches, where bank erosion ceases, debris input rate and, therefore, in-channel debris volumes would also be expected to decline. Debris will also become buried due to the increasing rate of alluvial deposition in Stage 4 and 5 reaches. For the same reasons a similar distribution would also be expected for the frequency of jams in each reach

Averaging the volume and frequency data for the survey reaches found in each stage produces the distribution of values shown in Table 5.1 (values are weighted according to the length of channel in each stage). It is evident that the trends through the values closely match those described above. The CEM categories, therefore, appear to be a better indicator of the relative

magnitudes of debris volume and jam frequency found in various channel reaches. The percentage differences shown in Table 5.1 are relative to 'equilibrium', Stage 1 reaches.

Outer bank erosion in active meanders was found to be the dominant mechanism for debris input. It might, therefore be assumed that channel sinuosity would be a good predictor of debris volume and the number of debris jams per unit reach length. In fact regression analysis of channel sinuosity against average volume of debris and average number of jams for all reaches surveyed produced r^2 values of only 0.05 and 0.02 respectively, when power functions were fitted. These coefficients of determination are not statistically significant.

While the trend of the functions is as expected, with more debris and a greater number of jams per unit reach length as sinuosity increases, the weakness of the relationships means that they have no predictive value. The explanation probably lies in the fact that a high sinuosity does not necessarily imply *active* meandering (ie where the channel has a sinuous planform which actively adjusts through outer bank erosion and point bar deposition). Active channel migration is difficult to quantify and requires knowledge of other parameters such as available stream power and bank material properties, or observation of channel planform change over time. There are insufficient data available at present to incorporate a reliable active meandering factor into the analysis.

Table 5.1 : Channel Evolution Model Stage as a measure of In-channel Debris Volume and Frequency of Debris Jams

CEM Stage	no. of reaches surveyed	reach length surveyed (m)	vol. of debris: av. per 100m sub-reach (m^3)	% difference from Stage 1	no. of jams: av. per 100m sub-reach	% difference from Stage 1
1	3	16000	5.4	-	0.22	-
2	5	17000	6.1	+13	0.48	+118
3	4	22000	9.1	+69	0.41	+86
4	3	13000	6.7	+24	0.38	+72
5	2	12000	0.8	-85	0.12	-45

5.3 Impact of LWD on Channel Processes

The impact of debris jams upon local scour and sedimentation processes has been analysed in stable, gravel-bed rivers (Abbe and Montgomery, 1996) but has not been studied in unstable sand bed rivers. Two important questions that need to be answered in the case of unstable, sand-bed rivers, are whether debris jams cause net scour or net sediment retention and whether there are any spatial trends in these processes. Answering these questions will enable river restoration programs to determine whether or not debris is of benefit to incising sand-bed rivers, in terms of aiding stabilisation and sediment retention and enhancing aquatic habitat.

Geomorphic field reconnaissance in the current research and in previous studies (Wallerstein and Thorne, 1994) indicates that the ratio of key debris length to average channel width and, therefore to some extent watershed area (using hydraulic geometry principles), is a good indicator of the impact that a jam will have upon flow field and hence channel morphology and sedimentation processes. A debris classification scheme, modified from a pool formation model (Robinson and Beschta, 1990) has been used to describe the observed impact of debris jams when moving downstream through the watershed network. This classification scheme is outlined in Figure 5.2a. Plate 3 shows an example of an underflow type jam on Worsham Creek (watershed area 10.3 km^2); Plate 4 shows an example of a Dam type jam on Lick Creek (watershed area 22 km^2); Plate 5 shows an example of a Deflector type jam on Fannegusha Creek (watershed area 46 km^2); and plate 6 shows an example of a Flow Parallel type jam on Harland Creek (watershed area 69 km^2). The observed frequency distribution of jam type for each reach is shown in Table 5.2. Watershed area for each reach is also shown to demonstrate the spatial trend in jam type.

It is evident that the jam type encountered with increasing watershed area matches to a reasonable degree, the distribution outlined in the simple schematic model in Figure 5.2a. Anomalies in the distribution in Table 5.2 can, for the most part, be explained by variations in local channel stability which affect channel dimensions and distort simple hydraulic geometry relationships. For the simple spatial model to be a good predictor of jam type it must, therefore, incorporate other predictive variables. A channel stability factor is necessary to account for unstable channel geometries that cannot be predicted by stable hydraulic geometry relationships. A further factor is also necessary to account for the degree of active channel migration. These factors are to be studied in future research.

Given that there is a weak spatial trend in jam type with distance downstream in the watershed, it is also reasonable to hypothesise that local scour and sediment retention at debris jams is also spatially predictable. Sediment retention and local scour caused by debris jams, averaged over a 100m channel length, are plotted against watershed area in Figure 5.1b.

The trends in Figure 5.1b are best described by quadratic regression relationships. These trends are statistically significant using one-tailed Pearson Product Moment tests, at the 0.05 confidence level. No statistically significant trends were found when stream power was correlated with sediment retention and scour.

The trends in Figure 5.1b can be explained because they mirror the impact of each debris jam classification type. Underflow jams, in small watersheds, interfere very little with the flow and,

therefore, do not have a high scour and sediment retention potential. Dam type jams, found further downstream, cause large volumes of sediment to be stored in backwaters, but also cause plunge pool scour. Downstream from Dam type jams, at Deflector jams, sediment is stored in the lee of jams as bar deposits, but the jams also cause flow to impinge on one or both banks, resulting in scour and bank collapse. Further downstream still, Flow-Parallel debris block the flow much less, so that energy dissipation, sediment retention and scour, are less effective.

The net impact of debris jams on the sediment budget in each reach, calculated as volume stored minus volume scoured, is shown in Table 5.2. These data were plotted against watershed area to determine whether there were any spatial trends between these variables. No, statistically significant relationship were found. It is important to note, however, that the data indicate that the balance between sediment scour and sediment retention caused by debris jams favors of net sedimentation. Thirteen of the channel reaches have a positive budget, one has a zero budget and only two have negative sediment storage budgets.

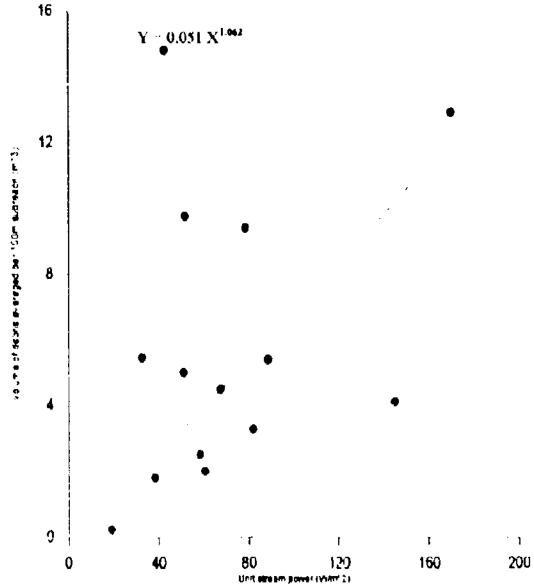
5.4 Jam Stability Through Time

Comparison of survey results between summer 1995 and summer 1996 shows there to be little change in the number and position of debris jams present in each reach. A total of 99 jams were surveyed, in 17 of the 23 reaches established in 1995. The six other reaches, all of which had agricultural riparian zones, were found to contain no significant debris accumulations. By summer 1996, 4 jams had been destroyed, of which one had been buried by sediment in a stage 4 reach, one had been manually removed for unknown reasons, and two had been broken up and transported downstream by the flow. Six new jams were identified in the survey of 1996, two of which were new beaver dams, while the other four were found to have formed by input of 'key' debris elements due to bank mass failure

Table 5.2 : Debris Jam Classification related to Watershed Area

Creek	Watershed area (sq. km)	Debris Jam Classification (number of occurrences) Underflow	Dam	Deflector	Parallel	Net sediment balance av. vol. per 100m (m^3)
Nolehoe	9.5	4	2	4	0	11.1
Worsham West	10.3	0	11	2	0	11.7
Lee	19.4	1	1	0	0	-0.5
Perry	20.9	4	3	0	0	2.9
Lick	22	0	0	1	0	10.7
Hickahala	23	0	2	1	0	6.2
Burney Branch	25	0	0	1	0	-1.9
Long	28	0	4	3	5	0.0
Sykes	31	0	1	4	2	8.1
Fannegusha	46	0	1	2	0	7.4
Abiaca 3	68	0	4	3	0	12.2
Harland 1	69	0	1	1	6	28.1
Otoucalofa	106	0	0	0	9	-1.8
Coila	108	2	0	0	5	28.4
Abiaca 4	113.9	0	0	0	2	17.3
Harland 23	129.5	0	0	0	7	1.2
Abiaca 6	256.4	0	0	0	2	3.6

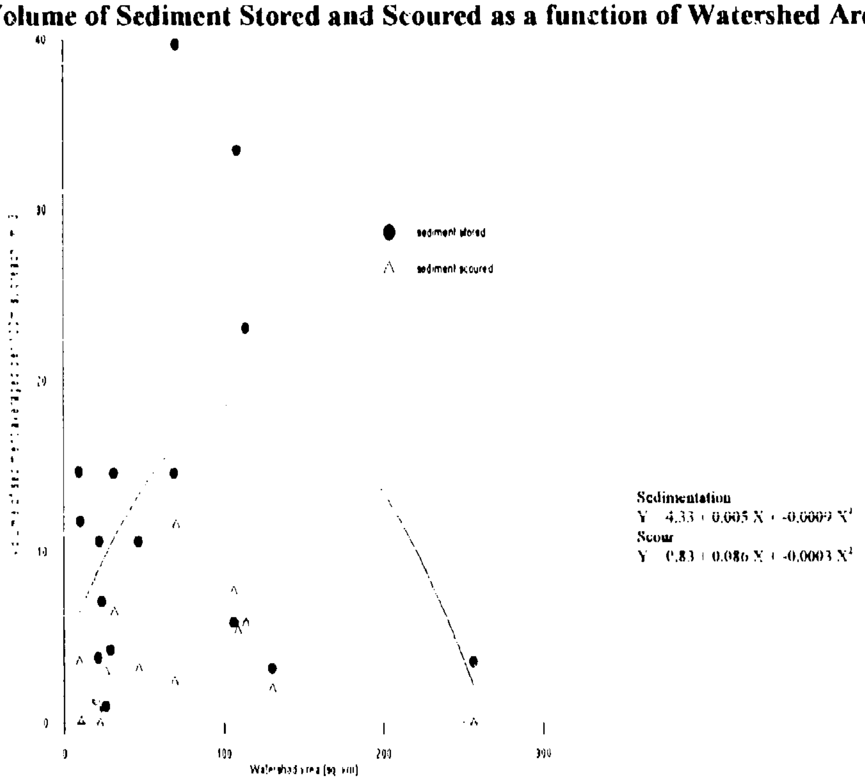
Figure 5.1a: Volume of Debris as a function of Stream Power



Pearson Product Moment Correlation Coefficient Analysis. One Tailed Test at 0.05

r^2	r	no. of observations	critical r	significant at 0.05 ?
0.31	0.56	14	0.45	Yes

Figure5.1b: Volume of Sediment Stored and Scoured as a function of Watershed Area



Pearson Product Moment Correlation Coefficient Analysis. One Tailed Test at 0.05

	r^2	r	no. of obs.	critical r	Sig. at 0.05 ?
Sedimentation	0.22	0.47	17	0.41	Yes
Scour	0.36	0.60	17	0.41	Yes

Figure 4.2 Debris Jam Classification Model

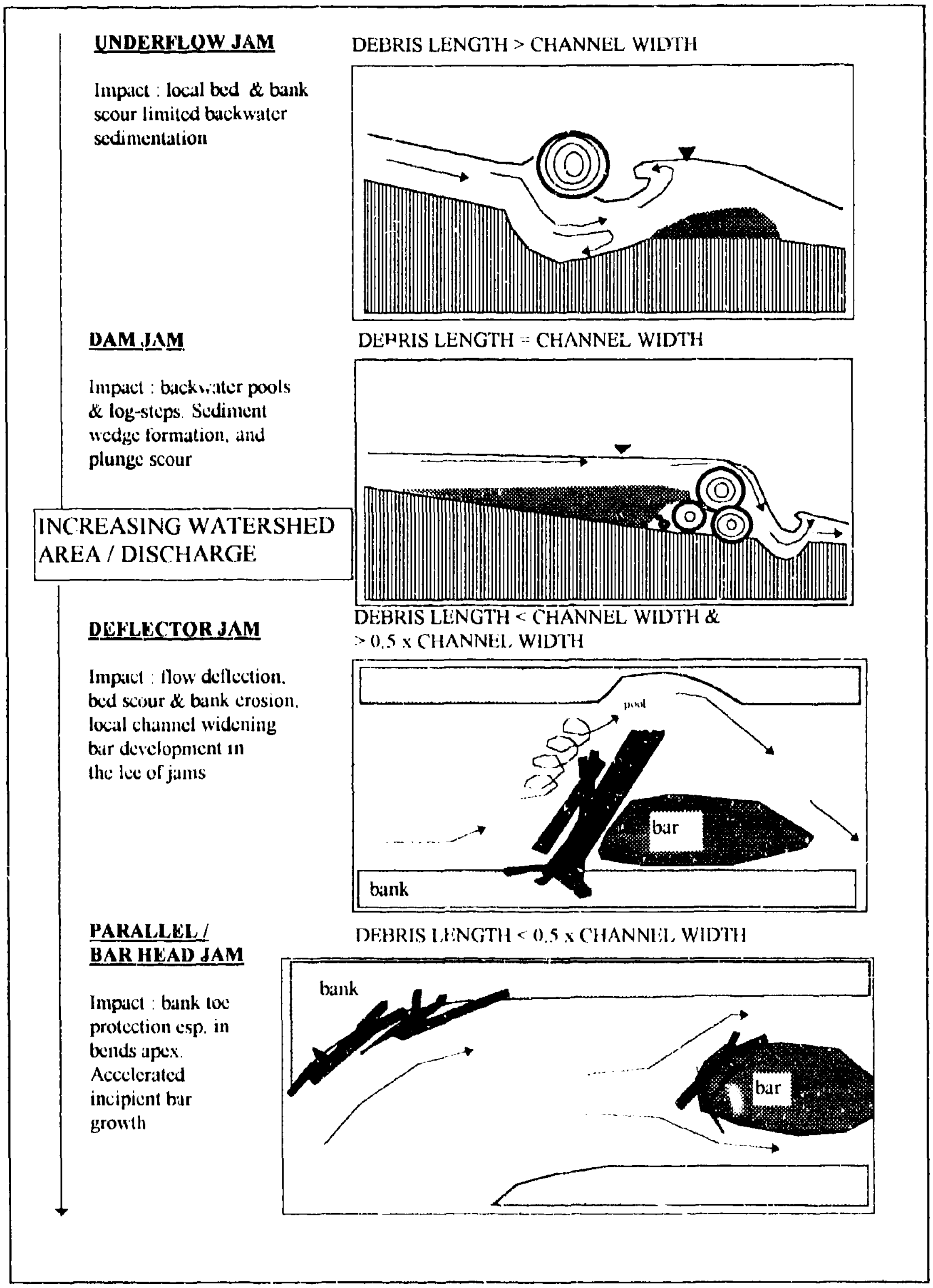


Plate 1 Debris input due to mass wasting of the bank on Harland Creek

Plate 2 Beaver Dam located in the sill of a Low Drop Grade Control Structure on Worsham Creek

Plate 3 Underflow Jam on Worsham Creek: watershed area 10.3 km^2

Plate 4 Dam Jam on Lick Creek: watershed area 22 km^2

Plate 5 Deflector Jam on Fannegusha Creek: watershed area 46 km^2

Plate 6 Flow Parallel Jam on Harland Creek: watershed area 69 km^2

5.5 DEBRIS JAM RESIDENCE TIMES: A THEORETICAL ANALYSIS

It is apparent from the preceding analysis of debris jam stability between 1994 and 1996 that, despite the fact that many of the channels are highly unstable and that the discharge regime is also very flashy, the majority of jams, have survived intack and remain at the location where they were first surveyed. It should be noted that several storm runoff events during the period 1993-94 in each of the three creeks exceeded the 2-year discharge values calculated by Watson et. al. (1993). If these events are taken as representative of an average year in the region it follows that debris jams are subjected to greater than channel-forming flows several time per year and yet remain in place. This finding can be verified in a more analytical fashion by examining the buoyancy and drag forces which act upon elements comprising a debris jam.

For a debris element to be lifted from the bed and floated downstream the buoyant force acting on the element must exceed the weight of the element.

The flotation force due to the pressure on the under surface of a submerged or partially submerged body is given by:

$$F_f = \rho_w gLA \qquad (5.1)$$

where , F_f = flotation force (N), ρ_w = density of water (1000 kg/m^3), g = gravitational constant (9.81 m/s^{-2}); LA = volume of the body submerged in water.

The weight force resisting flotation is given by:

$$W_t = \rho_s gla \qquad (5.2)$$

where, W_t = weight (N), ρ_s = density of the body (kg/m^3), la = total volume of the body (m^3)

To bring a object to the point of floating, these forces must be balanced:

$$F_f = W_t \qquad \text{or}$$

$$\rho_w gLA/\rho_s la = 1 \qquad (5.3)$$

The density of wood varies greatly and values between 400 and 800 kg/m^3 are suggested by Ashby & Jones (1980). The density of debris in a river will vary as a function of time and flow

history and as for example the wood becomes water-logged and then dries out. Hence, it is difficult to ascribe a precise density to debris jams per se. For the purposes of this analysis a value of 800 kg/m^3 is used on the assumption that the debris element has recently fallen into the river and is, therefore, not waterlogged.

The volume of the debris element in a jam varies greatly with time, but of greatest importance are the "key" debris pieces, which initiate the formation of jams and are largely responsible for their stability. An "average" large tree trunk in the region is of the order of 25m long with a maximum diameter of 1m yielding a volume of $25m^3$, this of course ignores the volume (and added density) of the root wad and of the smaller branches and leaves. For these parameters the flow depth required to float the element is:

$$1000 x 9.81 x LA / 800 x 9.81 x 25 = 1 = 9810 \times LA = 196,200$$

hence, LA = $20m^3$, and 20/plan area ($25m^2$) = 0.8m water depth.

This depth of flow is shallower than that occurring at all the creek sites at flow and so, in theory, even quite large trees could be floated several times per year. However, the filed evidence evidently indicates that this does not occur actually that often. Factors reducing the potential for tree floatation include, as already mentioned, increased wood density due to water-logging, the great weight of the root wad, grounding of trees on shallows, and snagging of the root wad and branches on the bank and other vegetation.

The second motivatinng force to consider is drag force on debris. Abbe and Montgomery (1996) use an analytical formula for describing flow past a bridge pier as an analogue to produce first order approximations for the force acting on debris elements. This formula is given as (see Chadwick & Morfett, 1986):

$$F_D = 0.5\rho_w C_D U^2 A \qquad (5.4)$$

where, F_D = drag force, ρ_w = density of water (1000 kg/m^3), C_D = drag coefficient, U = mean incident flow velocity, A = submerged area of the obstruction, normal to the incident flow.

Selection of a drag coefficient value is problematical. Petryk & Bosmajian (1975) use C_D = 1, for flow through flexible vegetation. Boundary conditions have the effect of increasing C_D, as

does the blockage ratio, Br, defined as the ratio of the width of the obstruction to the channel width, and Gippel et al. (1992) suggest that the effect on C_D becomes significant when Br >> 0.05. Conversely, surface roughness on the debris increases turbulence and thus reduces drag. Abbe & Montgomery use an average value of C_D = 1.55, as suggested by Rouse (1946), and this value will be used in the following analysis.

If a debris element is to be moved, the drag force must exceed frictional resistance provided by the immersed normal weight of the tree and contact with the channel bed. Interlocking between debris elements also greatly increases the resisting forces,.

For the sake of simplicity the forces on a simple "key" debris element will be assessed, having a length of 25m, diameter of 1m, and average density of 800kg/m^3. Interlocking forces are not examined due to the complexity of calculation, and the following analysis therefore provides a "worst case" analysis of force balance.

The drag force is determined assuming that the element lies in the channel with long axis at orthogonal to the flow, as has been found at most debris jam sites in the smaller creeks. Hence, it presents an area of 25m^2 normal to the incident flow. It is worth noting that even if we consider trees in a larger creek which have been rotated parallel to the flow and have a root wad normal to the incident flow, the area of this root wad will rarely exceed 25m^2 and, in any case, it is unlikely that the entire root wad would be submerged, even during over-bank flows. The assumptions made in this analysis should be tenable for large debris elements, whatever their orientation to the flow may be. The drag force on such an element has been calculated using mean flow velocity for the predicted 2-year discharge (Q2), (or bankfull discharge if Q2 is an out of bank flow), for each on the creek reaches, where data are available. The results are presented in Table 5.3.

Frictional resisting forces can be approximated to:

$$F_r = W_s \tan \phi \qquad (5.5)$$

where, F_r = frictional resisting force (N) W_s = submerged weight of the log (N), ϕ = angle of internal friction for the bed material (degrees).

The angle of internal friction for the bed material can be estimated from analysis presented in civil engineering texts such as Ashby and Jones (1996). The submerged weight of the log, based on the previous analysis of buoyancy force is however less than zero, making the

estimation of a resisting force by this method impossible. It is beyond the limits of this study to make a more in-depth analysis of force balance on LWD elements, however, from the observation of debris jams over the three year study period it can be concluded that jams which are initiated by large key debris elements, form semi permenant structures in the channel and are therefore significant agents of local channel geomorphological genesis and change.

Table 5.3 Drag Force on Simple Debris Elements

Creek	Mean flow velocity at bankfull flow (m/s^{-1})	Drag Force (kN)
Harland	1.19	27.55
Fannegusha	1.85	66.64
Abiaca 3	1.42	39.25
Abiaca 4	1.22	28.95
Coila	1.22	28.70
Abiaca 6	1.04	20.82
Nolchoe	1.98	75.92
Red Banks	1.77	60.46
Lee	0.40	3.17
Hickahala	1.66	53.62
Lower Hotopha	1.25	30.45
Upper Hotopha	0.95	17.63
Marcum	1.82	64.46
Otoucalofa	1.84	65.42
Sarter	1.58	48.59
Perry	1.23	29.53
Sykes	0.87	14.72
East Worsham	1.69	55.27
Middle Worsham	1.56	46.96
West Worsham	1.85	66.10
James Wolf	1.52	44.47
Long	1.27	31.22

6 LARGE WOODY DEBRIS MANAGEMENT PROGRAM (DMP)

The relationships between LWD and channel processes have been incorporated into a LWD Management Program (DMP). Version 2.0 of this program is included with this report on a disk.

Version 2.0 is an updated version of the program to that included with the Project R&D 7258-EN-09, submitted to the US Army Corps of Engineers, June 1995 (Wallerstein, 1995).

The program predicts the likely jam type in a given reach, determines its impact upon the channel and outlines an appropriate management strategy. Inputs variables are those found to be most critical in the analysis of LWD in the fluvial system and include channel width (determined from a catchment area function), average riparian tree height, reach sediment type and the riparian land-use type. The ratio of tree height to channel width is used to define the debris jam type likely to be present, with the precise limits of each classification determined from the empirical relationships. Sediment diameter is used to give an indication of the jam's potential to induce backwater sedimentation or downstream bars. Debris jam types are classified using a scheme modified from Robinson & Beschta (1990), described in Wallerstein & Thorne (1994). Jam types are divided into **Underflow, Dam, Deflector** and **Flow Parallel**. Program output takes the form of a text file which describes indicated likely jam-type and offers advice on appropriate in-channel LWD management strategies for this situation. While the management strategies are based solely on theoretical considerations, the program never-the-less provides a framework for future model development as empirical relationships between the variables are better characterised. A flow diagram of the computer program is shown in figure 6.1.

6.1 GIS Interface

The program has also been linked to a GIS (Geographical Information System) data input system which was constructed by Peter Cheeseman, a masters student at Nottingham University as part of this project (Cheesman, 1995). The work was carried out to demonstrate the potential for using GIS as a platform for data input to expert systems designed to aid engineers with river basin management.

The GIS was constructed in ARC INFO using data layers, supplied by the WES Intergraph data-base, for the Abiaca Creek watershed and provides both automatic data input for the necessary variables and a platform for running the program. This watershed was selected

because it contains four of the debris survey reaches being monitored in the current research. The theoretical model could, therefore, be tested against the empirical data results from the field studies, validated and further developed.

A full description of the GIS model construction is presented in Appendix A.

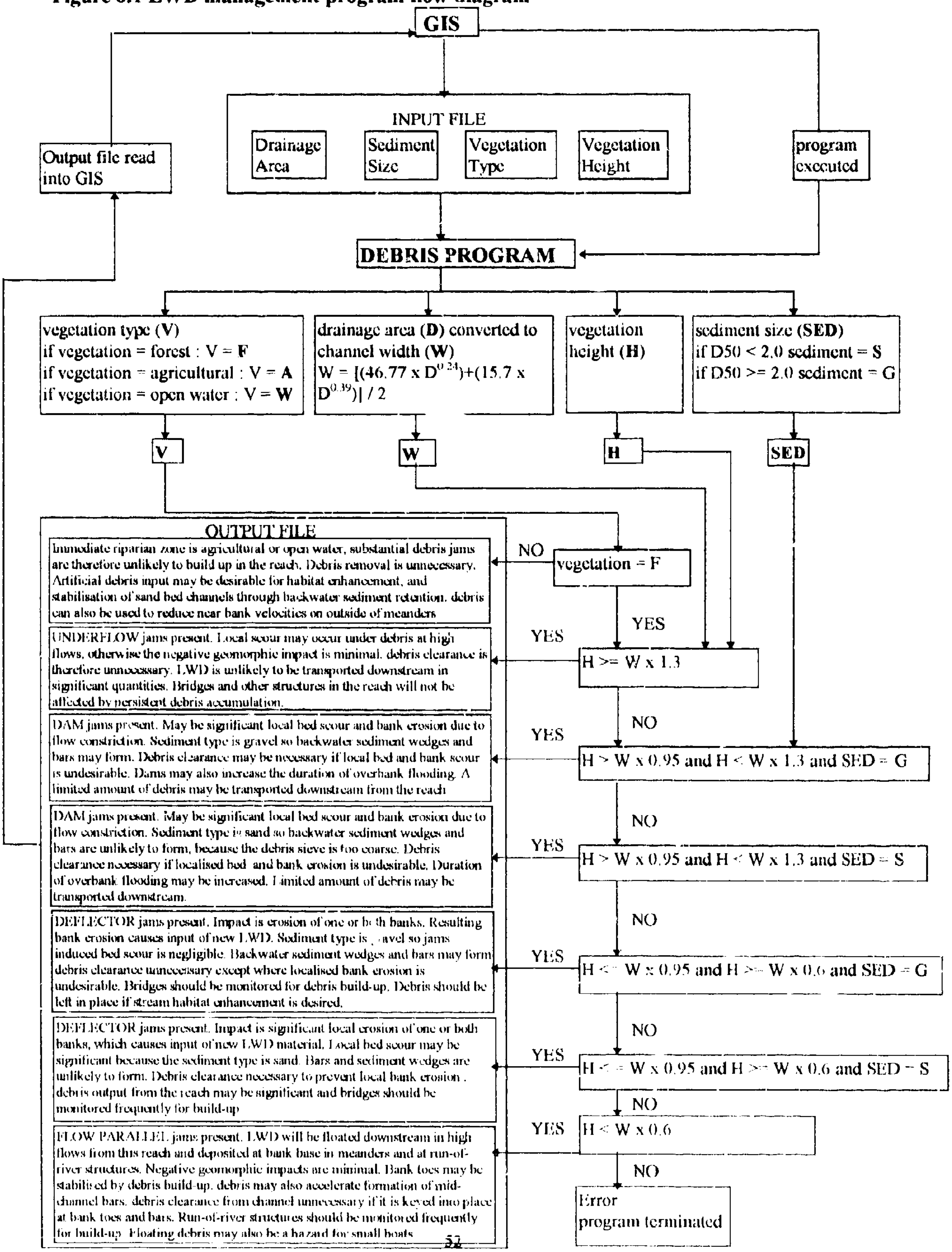
The GIS user interface for the DMP is also now available for use and can be obtained upon request from nick@geography.nottingham.ac.uk

The program runs on the UNIX version of ARC INFO and requires approximately 98 mb of memory to install.

The GIS is composed of four layers: the drainage network; road network; landcover; and, channel sediment type. There is also a terrain model which is used to calculate drainage basin area. The system incorporates a menu driven interface used to display the data layers and perform analyses. On-line help files are also included. The analysis is performed by simply placing the cursor on the area of interest and clicking the mouse. The system then extracts the relevant input data from the database for that location and passes them to an input file. The debris management program is then automatically activated and reads the input file, calculates the results and produces an output text file. This file is then read back into the GIS and displayed on the computer screen.

This management model is simple to operate and provides a framework for future development as empirical relationships between variables are better characterised.

Figure 6.1 LWD management program flow diagram



6.2 Testing the Model

The model has been tested against the geomorphic data obtained for each reach in northern Mississippi. In the test run channel width was determined using the linear regression function obtained using the DEC data from Watson et. al. (1993). The formula for this function is:

$$y = 8.7X^{0.23}$$

where, y = mean channel width (m), and X = drainage basin area (km^2).

The r^2 value is 0.34. This result is statistically significant at the 95% level.

The results of this test are displayed in table 6.1 and are compared with the distribution found in the field data. No underflow type jams are predicted by the model. Nolehoe and Worsham Creeks are predicted to have predominantly dam type jams. Ten creeks are predicted as having deflector-type jams, while the largest five creeks are predicted to have flow-parallel jams. This distribution is in reasonable agreement with the distribution found in the filed data, the predominant jam type being predicted correctly for 11 of the 17 reaches.

The differences between predicted and observed jam types can, for the most part, be explained by variations in local channel stability, which affect channel dimensions, but are not accounted for in the simple model. Nolehoe Creek, for example, has a large number of deflector type jams rather than the expected underflow jams despite having the smallest drainage area and, therefore, the narrowest predicted channel width. The reason for this anomaly probably lies in the fact that Nolehoe Creek is highly unstable (stage 2 type reach in Schumm et al.'s Channel Evolution Model (CEM)) and is, therefore, deeply incised. Large trees close to the channel edge are therefore prone to collapsing into the channel to surcharge, which results in mass bank failure. Consequently, debris vertical angle (beta angle) is greater than zero, making the span of fallen trees less than they would otherwise be if the debris lay horizontally.

In Long Creek there is a disproportionate number of parallel type jams because much of the debris found in the reach is 'paleodebris': that is material reintroduced into the channel from erosion of old alluvial deposits containing debris, which has broken down over time and is, therefore, found in great abundance in individual elements of short length.

Abiaca Creek, site 3 is predicted to have predominantly deflector-type jams, but actually has a majority of dam type jams. The reason for this discrepancy is because channel width varies considerably about the mean within the reach, with wide bend sections separated by much shorter, narrower straight reaches which contain all the dam-type jams.

Coila Creek, which has an even greater average width than Abiaca (3), contains two underflow type jams. These have formed because the channel reach has re-stabilised (CEM stage 5) and the jams are located in a short, narrow reach which has been narrowed by berm formation.

It is evident, therefore, that for the model to yield improved predictions of jam type, it must incorporate further predictive variables. A channel instability factor should be added to account for the deviation of channel geometry from that predicted by the simple hydraulic geometry relationship for stable conditions. Also, an additional factor is necessary to indicate the rate and distribution of lateral channel migration.

Functions could also be included to predict the volume of debris and number of debris jams likely to be found in a reach, using regression relationships derived from observations of debris volume and number of jams per unit reach length as a function of drainage basin area.

Channel instability and lateral migration factors could also be used to predict the volume of debris likely to be input to a reach by estimating the rate of bank retreat. The input rate should be reflected in the storage volume and frequency of jams. An attempt is made in section 6.3.2 to incorporate reach debris volume and number of jams per unit reach length as prediction factors.

The model also attempts to predict, in a simple manner, the impact that debris jams have in retaining sediment load, causing bed scour and generating bank erosion. This estimate is based solely on the median sediment grain-size. The net sediment balance volumes (average sediment stored at each jam minus average volume of sediment scour by each jam) for each reach (see table 5.2), compared with predicted relative sedimentation potential in Table 6.1 show no significant correlation. Hence predictive potential in the model is purely descriptive, making comparison with field data rather tenuous. It may be concluded that reach grain-size alone is too simple a measure of jam sedimentation potential. A measure of the energy available to transport the sediment load, such a stream power, in combination with sediment characteristics is likely to be a more successful predictor. Empirical models of flow dynamics and scour around in-channel obstructions are more likely to give at least order of magnitude predictions for scour and sedimentation potential at debris jams. The use of a such model is discussed in section 6.3.3.

Sedimentation processes are also affected by the vertical angle of the debris elements. If, for example, debris is steeply inclined more bedload is likely to pass through the jam than if the debris lies horizontally on the channel bed. This factor could be accounted for in further developments of the model by incorporating a width-depth ratio factor which predicts 'true'

debris length to channel width ratios and the percentage of channel cross-sectional area blocked. An attempt is made to incorporate a beta angle factor in section 6.3.1.

Limitations to the model include the fact that jam-type prediction is very much dependent on the width function selected and, therefore, the goodness of fit of the hydraulic geometry relationship. To make the model more robust it may be necessary to include channel width as a variable input by the user, rather than as a factor predicted by spatial functions based on upstream drainage area. Alternatively, it may be more realistic to make jam-type a function of CEM stage, because this has strong control over channel geometry.

Table 6.1 Model Results

Creek	Predicted channel width (m)	Debris Jam Classification				Jam Type Found in Field				Sediment storage potential
		Underflow	Dam	Deflector	Parallel	Underflow	Dam	Deflector	Parallel	
Nolehoe	13.7		+			4	2	4	0	high
Worsham West	14		+			0	11	2	0	low
Lee	16.8			+		1	1	0	0	low
Perry	17.1			+		4	3	0	0	low
Lick	17.4			+		0	0	1	0	low
Hickahala	17.7			+		0	2	1	0	low
Burney Branch	18.3			+		0	0	1	0	low
Long	18.8			+		0	4	3	5	low
Sykes	19.3			+		0	1	4	2	low
Fannegusha	21.6			+		0	1	2	0	low
Abiaca 3	24.2			+		0	4	3	0	low
Harland 1	24.3			+		0	1	1	6	low
Otoucalofa	27.5				+	0	0	0	9	moderate
Coila	27.6				+	2	0	0	5	moderate
Abiaca 4	28.1				+	0	0	0	2	moderate
Harland 23	29.2				+	0	0	0	7	moderate
Abiaca 6	35.8				+	0	0	0	2	moderate

6.3 Revisions to the Model

The results of the tests described above indicate that the initial theoretical model is currently limited as a practical predictive tool, but has the potential for improvement in predicting debris jam type and associated channel geomorphology if additional factors are incorporated. Improvements to the model, outlined below, utilise further theoretical concepts and empirical results from the field data results.

6.3.1 Debris Beta Angle

It was noted in section 6.2 that if the beta angle of key debris was much greater than zero degrees (debris lying horizontal on the channel bed) the jam type might not be predicted correctly (such as in the case of Nolehoe Creek). Beta angle will also affect the extent to which floating debris is trapped by the jam, the flow field and, therefore, scour and sedimentation

processes. Beta angle can be predicted by assuming that key debris elements stand close to the channel bank before they fall in and then topple forward into the channel, forming the hypotenuse of a right-angle triangle with, bank height, and the actual width spanned by the element being the other two sides. A better prediction of jam classification (channel width to tree height ratio) can then be determined using:

$$w = \sqrt{(T^2 - B^2)} \qquad (6.1)$$

where, w = actual bottom width spanned by debris (m), T = tree height (m) and B = bank height (m).

This formula can be directly incorporated into the model to improve predictions debris jam-type. Correlation between beta angle, scour and sedimentation volumes for each reach could in theory be used to improve prediction of jam impact on sediment processes. No statistical correlation between beta angle and either the retained sediment volume or the scour volume was found, however, and it is therefore not meaningful to add any relationship between these factors to the model.

6.3.2 Prediction of Debris Volume and Number of Jams

Prediction of the average number of debris jams and average volume of debris in a reach would be beneficial in directing LWD management activities to those reaches where debris build up is significant. The conceptual relationships between these parameters and drainage basin area and unit stream power were outlined in Chapter 5 Analysis of the field data revealed statistically insignificant, correlations for all these relationships, except stream power and debris volume. It must be concluded that debris volumes and number of jams per unit reach length cannot be accurately predicted using simple regression formule.

In fact, reach stability and channel sinuosity are probably important controls of debris volume and the occurrence of jams because these factors to a great extent determine the rate of debris input. Examination of the distribution of average debris volumes for each stage of the Channel Evolution Model is discussed in chapter 5 and summarised in Table 5.1.These values can be included in the model to improve prediction of the magnitude of debris build-up relative to that found in stable reaches. Reach stability has been added to the model as a further input variable. The user must, therefore, be familiar with the Channel Evolution Model in order to make an assessment of the reach in question based upon width/depth ratios, bank stability and depth of

sediment in the channel bed. Stability can also be inferred using the model itself on the basis of the average width/depth ratios which characterise reach type (see width/depth ratios in table 3.1). This classification is not straight forward, however, as ranges of width/depth ratio associated with particular CEM stages overlap and the model must be given a further parameter, such as depth of sediment in the channel or average bank angle to allow it to discriminate between evolution stages.

6.3.3 Prediction of Scour and Sedimentation Processes

When the initial, conceptual model was developed there was no literature base that dealt specifically with scour and sedimentation processes around LWD. The simple approach adopted in the model for estimating the extent of scour and sedimentation processes proved to be rather inadequate because of the lack of an empirical basis.

Recent research by Abbe and Montgomery (1996) partially addresses this issue by attempting to predict channel scour associated with jams based upon experimental and observational studies of scour around bridge piers and abutments. According to Raudkivi (1990), scour processes can be divided into:

1) General scour which occurs due to increasing discharge or slope, irrespective of an ;
2) Constriction scour, which occurs due to a reduction in channel cross-sectional area, and;
3) Local scour, which occurs due to an obstructions direct effect on the flow field.

Abbe and Montgomery approximate local scour around debris in a large river using a model developed by Liu et al. (1961) which predicts clear water scour around an abutment:

$$\frac{d_{ls}}{h} = 2.15\left[\frac{La}{h}\right]^{0.4} Fr^{0.33} \qquad (6.2)$$

where, d_{ls} = depth of local scour (m), h = flow depth (m), La = abutment length (m), Fr = U / $(gh)^{0.5}$, and U = mean flow velocity (m/s^{-1}).

Constriction scour is approximated using an empirical model presented by Laursen (1963):

$$d_{cs} = h\left[\left(\frac{T_o}{T_c}\right)^{0.429}\left(\frac{wb1}{wb2}\right)^{0.857} - 1\right] \qquad (6.3)$$

where d_{cs} = depth of constriction scour (m), τ_b = bed shear stress (N/m^2), τ_c = critical bed shear stress (N/m^2), wb1 = unobstructed flow width (m), and wb2 = constricted flow width (m).

Total scour depth due to an obstruction is calculated by Abbe and Montgomery as the sum of scour values from equations 6.2 and 6.3.

It was found that the values predicted by these equations significantly overestimated scour depths in the study reach (Queets River, Washington State) of an armoured, gravel-bed river. Experimental work by Raudkivi and Ettema (1973) showed that scour depths were greatly influenced by sediment sorting and Raudkivi (1990) presents a graphical method for adjusting scour prediction that predicts adjusted scour depths as a function of the standard deviation of the reach-averaged sediment grain size. When this adjustment factor was applied to Queets River data, the total estimated scour was found to be within 3% to 17% of pool depths observed in the study reach. These two equations were incorporated into an updated version of the model because they appear to provide reasonable approximations for prediction of scour depths at debris jams. Given the type of debris accumulations studied in the Queets River, equations 6.2 and 6.3 are probably best suited to describing scour conditions around flow parallel and deflector-type jams, where the channel width is considerably greater than the obstruction width. Following the successful use of these models by Abbe and Montgomery, other scour models were explored to attempt to approximate scour conditions at dam and underflow type jams.

If the jam type encountered in a reach is of the 'dam' type and fully blocks the channel width, constriction and local scour are unlikely to be significant. Instead, scour may occur downstream of the jam due to a jet of water plunging over the dam 'weir'. Raudkivi (1990) discusses several methods for predicting plunging jet scour from free overflow, flip buckets and similar hydraulic structures. The equation developed by Mason and Aruumugam (1985) (see Raudkivi, 1990) should be appropriate for approximating plunge scour at a dam-type jam, however, because it satisfies Froude- law scaling. The model is expressed as

$$D = 3.27\left[\frac{q^{0.6}H^{0.05}h^{0.15}}{g^{0.3}d_m^{\ 0.1}}\right] \qquad (6.4)$$

where, D = flow plus scour depth (m), q = unit discharge in the jet ($m/s^{-1}/m$), H = head difference between reservoir crest and tailwater surface (m), h = tailwater depth (m), g = gravitational constant (9.81 m/s^{-2}), and d_m = mean grain size (m).

Scour at underflow jams is rather more difficult to predict as the jam will only impinge on the flow above a certain flow stage, depending upon the height of the debris element above the bed (this need not necessarily be bank top height). A formula is proposed by Shalash (1959), (in Raudkivi (1990)), to determine the scour caused by an underflow jet, but this model assumes that there is a solid horizontal apron on the channel bed which extends downstream of the obstruction by a minimum of 1.5 times the approach flow depth. The model is, therefore, not applicable to channels with erodible beds. Scour at underflow jams cannot be adequately represented by empirical formula that have been developed to date, and it remains for future studies to model this phenomenon.

Estimation of the volume of sediment stored by a debris jam is a more complex problem, and no research has been found which attempts to model local distribution and volumes of sediment storage in alluvial channels. Sediment is stored at two distinct locations around debris jams. The first storage zone is in the zone of low shear stress downstream of the obstruction where streamlines are separated. The second storage zone is upstream of jams, but is only significant if the jam blocks a sufficient percentage of the channel cross-section to cause a backwater effect. Sedimentation in this backwater zone is similar to that in a reservoir. Reservoir sedimentation has been found to be dependent upon sediment size and grading, size and shape of the reservoir, inflow and outflow rates, and type and location of the outflow. The formation of deltas in reservoirs, let alone in local channel reaches is difficult to model and has mostly been dealt within a qualitative manner, although a few analytical models have been attempted (see, Chen et al., 1978). Prediction of backwater and bar sedimentation at jams is, therefore, a complex problem and it is beyond the scope of this thesis to develop analytical models to adequately describe it.

6.3.4 Refining the Model

The following revisions were made to the model in the light of the preceding analysis and discussion.

- **Width Input**

Average channel width may now be entered into the model using one of three methods. The first option is to use the hydraulic geometry function derived by Schumm et al. (1984) for

channels in northern Mississippi. The second option is to enter a user-defined hydraulic geometry function of a simple power form ($Y = aX^b$). The third option is to enter an observed value for the width directly.

- **Debris Length**

Equation 6.1 is used in the modified model to determine the effective debris length in the channel, if the jam type is determined to be other than the underflow type. This calculation requires a channel depth value which, like the channel width, may be entered into the model using any one of the three options described above. The hydraulic geometry function defined by Schumm et al. (1984) for channel depth in quasi-equilibrium reaches in northern Mississippi is:

$$\text{Average depth (feet)} = 12.27 \text{ drainage area}^{0.05} \tag{6.5}$$

- **Debris Volume and Jam Frequency**

Reach stability, defined by the Channel Evolution Model (Schumm et al., 1984), is used to predict the approximate volume of debris and the approximate number of debris jams to be found per 100m reach (see table 5.1). The channel evolution stage may be entered directly by the user, or the model can predict reach stage on the basis of the calculated width/depth ratio and the mean depth of sediment on the channel bed. The width/depth ratio and sediment depth ranges for each stage, which are incorporated into the model, are taken from the field data analysis presented in table 3.1. The sediment thickness variable is entered by the user and must be based on field measurement or estimation.

- **Scour Prediction: deflector and flow-parallel jams**

For deflector and flow parallel jams maximum local and constriction scour is predicted using equations 6.2 and 6.3. Total scour is calculated as the sum of these figures. Mean flow velocity, required to calculate the Froude number in equation 6.2, is determined using the 'law of the wall' equation for turbulent flow (see Chow, 1959, pg. 201):

$$\frac{v}{v_*} = \frac{1}{k} \ln \frac{d}{d_0} \tag{6.6}$$

where, v = time averaged velocity at elevation d above the bed (m/s^{-1}), v_* = shear velocity = $(gds)^{0.5}$ (m/s^{-1}), g = gravitational constant (9.81 m/s^{-2}), s = bed slope, k = von Karman constant = 0.4, and d_0 = boundary roughness height = $30/D_{65}$ (approx.) (m).

The depth value, d, is multiplied by 0.4 in equation 6.6 to obtain v, the mean depth- averaged velocity. D_{65} is substituted by D_{50} in the model to reduce the data input required by the user. La is taken as the effective debris length in the model if the jam type is dam or deflector and as average root wad diameter if the jam type is flow parallel. Scour is not calculated if the jam type is underflow, because the model is only applicable to obstructions resting on the channel bed.

In equation 6.3, the critical bed shear stress (T_c) is determined using the following formula, suggested by Pitlick (1992):

$$T_c = \theta\ (\rho_s - \rho_w)\ g\ D_{50} \qquad (6.7)$$

where, θ = critical Shields Parameter value (approx. 0.05), ρ_s = density of sediment, taken to be approx. 2650 kg/m^3, and ρ_w = density of water = 1000 kg/m^3.

Bed shear stress (T_o) for the flow depth being modelled is calculated as:

$$T_o = \rho_w\ g\ R\ S \qquad (6.8)$$

where, R = hydraulic radius = (A/P) (m), A = mean channel cross-sectional area (w x d) (m), and P = wetted perimeter = (2 x d + w) (m)

The obstructed flow width is calculated as channel width minus effective debris length if the jam type is deflector, and as channel width minus root wad diameter if the jam type is flow parallel. If the jam type is underflow constriction scour is not calculated because the model was developed only for obstructions resting on the channel bed.

It is left to the user to adjust pool scour and constriction scour values using the method suggested by Raudkivi (1990, pg. 251) if bed armouring processes are thought to be significant.

- **Scour Prediction: Dam-type jams**

For dam type jams, scour depth is calculated using equation 6.4. Unit discharge is calculated as V x flow depth. H, the head difference across the dam, is taken to be approximately equal to

the jam height minus tailwater depth. Jam height is simply taken as diameter of the key debris element. The modified model, therefore, requires the input of mean tree trunk diameter. The tailwater depth (h) is very difficult to estimate and is set somewhat arbitrarily in the model to be 20% of the approach flow depth, giving 'worst case' scour conditions. The mean sediment diameter (d_m) is replaced by d_{50} in the model. Depth of scour is D (total flow and scour depth) minus tailwater depth.

- **Scour Prediction: Underflow-type Jam**

For underflow type jams scour is not calculated owing to the difficulty in applying any of the equations presented in the literature.

7 HYDRAULIC SIGNIFICANCE OF LWD

A comprehensive investigation of the hydraulic effect of LWD in rivers has not to date been documented. However, some studies have investigated the effect of LWD on channel roughness, runoff hydrographs, velocity distributions and the water surface profile.

7.1 Effect of LWD on channel roughness

The Manning's equation generates a resistance coefficient that represents all sources of roughness in the channel. This equation is widely used by river engineers who select values of "n", from personal experience, tables in Chow (1959) or photographs in Barnes (1967). The range of "n" factor in normal channels is between 0.025 and 0.15. For heavily congested streams less than 30m wide n ranges from 0.075 to 0.15. Irregular and rough reaches of large streams have values of "n" from 0.035 to 0.10.

$$n = \frac{R^{2/3} S^{1/2}}{V} \qquad \text{or} \qquad n = \frac{1.49}{V} R^{2/3} S^{1/2} \qquad (7.1)$$

where, n = Mannings roughness coefficient, R = hydraulic radius (m), S = energy slope, V – mean velocity (ms^{-1}), 1.49 = conversion to fps units.

Rather than Using Manning's "n", the more theoretically based Darcy-Weisbach flow resistance equation was used (Richards, 1982) which is expressed as:

$$f = \frac{8gRS_w}{V^2} \qquad (7.2)$$

where, f = Darcy-Weisbach friction factor, R = hydraulic radius (m), and S_w = energy slope

The effect of LWD on flow resistance varies as a function of relative flow depth of. Bevan et al. (1979) found that when LWD is large in relation to flow depth the roughness coefficient is extremely high (Manning's n >1). As LWD becomes increasingly submerged it exerts less influence on flow resistance. Shields and Smith (1992) measured a large decrease in Darcy-Weisbach friction factor as discharge increased, and also observed that friction factors, for cleared and uncleared reaches converged at high in-bank flows. Indirect evidence to support these findings is provided by investigations of downstream hydraulic geometry which show that roughness generally decreases as

channel size increases (Wolman, 1955). Petryk and Bosmajian (1975) derived an equation to predict Manning's "n" as a function of density of vegetation in the channel, hydraulic radius, Manning's "n" due to boundary roughness and a vegetation drag coefficient.

$$n = n_b \sqrt{1 + \frac{Cd \sum Ai}{2gAl} \left(\frac{1.49}{n_b} \right)^2 \left(\frac{A}{P} \right)^{2/3}} \tag{7.3}$$

where, n_b = Manning's boundary roughness coefficient excluding the effect of vegetation, Cd = drag coefficient for vegetation (assumed to be 1), Ai = projected area of the ith plant in the streamwise direction (m^2), A = cross-sectional area of flow (m^2), L = length of the channel reach being considered (m), and P = (m).

In this formula the expression CdΣAi/AL represents the density of vegetation in the channel. Gippel et. al. (1992) note that a problem with this formula lies in selecting a value for the drag coefficient, Cd. Petryk and Bosmajian assumed a value of 1, but this strictly only applies to cylinders in infinite flow. In streams, interference from nearby obstructions and the effect of blockage on the drag coefficient must also be considered.

Manning's equation is, however, inapplicable in situations where there is a high degree of obstruction in the channel, particularly where n >1. It was developed empirically to describe open channel situations with fully turbulent flow, where friction is controlled primarily by skin friction at the channel boundary. The equation attaches significance to the hydraulic radius which may be irrelevant if the channel is heavily choked with LWD.

Smith and Shields (1992) studied the effects of varying levels of LWD density on the physical aquatic habitat of South Fork Obion River, Tennessee, USA. Two secondary objectives in this study were to develop and demonstrate a method for quantifying LWD in a given reach and to relate the quantity of LWD to reach hydraulics. An approach similar to that used by Petryk and Bosmajian (1975) was used to calculate the effect of LWD on channel roughness. The LWD density in a reach was calculated using the following formula:

$$DA = \sum_{i=1}^{n} \frac{A_i}{A} L_r = (1 / L_r) \sum_{j=A}^{D} F_{bj} \sum_{k=1}^{3} N_{j,k} F_{wk} \tag{7.4}$$

where, DA = LWd density (m^2), n = total number of LWD formations in the reach, A_i = area of the ith debris formation in the plane perpendicular to flow (m^2), A = reach mean flow cross-sectional area (m^2), L_r = reach length (m), F_{tj} = formation type weighting factor for jth formation type, $N_{j,k}$ = number of type j LWD formations in Kth width category, and F_{wk} = weighting factor based on LWD formation width category.

Appendix B presents the Smith & Shields (1992) survey form and shows how to calculate the weighting factors.

In a channel reach where LWD plays a major role in flow resistance, total resistance can be expressed as:

$$f_t = f_b + f_d \tag{7.5}$$

where, f_t = total Darcy-Weisbach friction factor, f_b = boundary friction factor excluding LWD effects, and f_d = friction factor due to LWD.

Total head loss is the sum of a boundary friction loss and a LWD blockage loss, as follows:

$$h_L = S_E L = \frac{\left[\left(f_b L / 4R\right) + K_d\right] V^2}{2g} \tag{7.6}$$

where, h_L = total head loss (m), S_E = slope of the energy gradient, and K_d = dimensionless loss coefficient (dependent upon LWD density).

The energy gradient (S_E) can be calculated using a total friction factor from the Darcy-Weisbach equation:

$$S_E = \frac{f_t V^2}{(8gR)} \tag{7.7}$$

Substituting this expression for S_E into equation 6 gives:

$$f_t = f_b + \frac{4RK_d}{L} \tag{7.8}$$

therefore:

$$f_d = \frac{4RK_d}{L} \tag{7.9}$$

The ratio K_d/L may be expressed in terms of the LWD density as:

$$K_d / L = DA \tag{7.10}$$

Smith and Shields calculated values for f_b using curves developed by Alam and Kennedy (1969), hydraulic parameters determined from dye tracer tests in the LWD reaches (which provide direct discharge and velocity estimates (Richards 1982)), and the median bed grain size determined from sieve analysis. Values for f_d were then calculated using equations 7.3, 7.9 and 7.10. They then compared computed values of f_t with values measured using dye tests.

The results of their study showed a reasonable positive correlation between the measured and computed friction factors. However, they recognised that considerable refinement and site-specific adaptation may be required, and that the method does not account for local energy loss because of bends or flow expansion and contraction at bridges, debris dams or riffles. The method does have a sound theoretical basis, however, and could be usefully employed in future research into the hydraulics effect of LWD.

7.2 Effect of LWD on velocity distribution

LWD clearly influences the direction and magnitude of flows currents within stream flow, but few data have been documented in the literature. Swanson (1979) produced detailed maps of debris jams indicating flow orientation with directional arrows. Smith and Shields (1990) reported that the removal of LWD from a river 18-23m wide 3.5 to 4.5 m deep produced more uniform flow, with less of the channel occupied by eddies or regions of reduced velocity. The local impacts of LWD on flow field and velocity distribution are not well established.

7.3 Effect of LWD on stage/discharge relationships, the hydrograph and flood frequency

LWD is often removed because it is believed that this will achieve a significant reduction in channel roughness which will produce a higher mean velocity and thereby increase in-bank channel flow capacity. There is some evidence to support this assumption. For example Smith and Shields (1990) measured the mean velocity in two cleared reaches of a river to be 0.04 m/s and 0.34 m/s respectively. In an uncleared reach of the same river the mean velocity was 0.27 m/s. MacDonald

and Keller (1987) also found that there was a local increase in velocity by up to 250% as a result of LWD removal and a decreased sinuosity of the low-flow thalweg. According to Gippel et al. (1992) the Murray-Darling Basin Commission calculated a theoretical reduction in water level of 0.3-0.4 m after the removal of approximately 200 snags per kilometre. However, later analysis of flow records indicated a reduction of only 0.2 m. In theory, there should be a statistical reduction in the magnitude and frequency of overbank flooding where debris is removed from a channel because of the increased channel capacity. Bodron (1994), used a dynamic routing model to demonstrate changes in both stage and duration of flood events before and after LWD removal, using Manning "n" values calculated in the study by Smith and Shields at South Fork Obion River, west Tennessee. Despite the fact that the increase in channel cross-sectional area due to LWD removal was ignored, small reductions in flood height and duration were calculated based solely on the change in Manning's "n". Bodron also noted that flood stage would be reduced further if sediment accumulations at each jam site had been removed. However, according to Gippel et al (1992) many claims that this effect has been achieved lack any hard supporting evidence. Counterclaims also lack supportive evidence, because of the difficulty of isolating the hydraulic effect of LWD removal. It is even possible that LWD removal might increase downstream flood peaks, because in the smoother channel the flood wave is less attenuated.

Gregory et. al. (1985) found that LWD ponds water which results in an increase in water depth and a decrease in velocity which, at low flows, influences travel time significantly. At high flows, however, the ponding effect of LWD is drowned out. Shields and Nunnally (1984) noted that because large accumulations of LWD have a damming effect on the flow which locally elevates the base level they can be treated as geometric elements within the channel, rather than simply as roughness elements, in backwater profile computations.

7.4 Modelling the hydraulic effect of LWD

Most studies of resistance to flow in rivers have concentrated on small-scale roughness, especially skin friction offered by bed sediments, where the size of the roughness element is small compared to the flow depth. LWD, on the other hand, represents a form of large-scale roughness for which skin friction is small compared to form drag (Petryk and Bosmajian, 1975). Flow conditions associated with the presence of LWD in streams varies from sub-critical to super-critical depending on the dimensions of the LWD and the depth of water.

Gippel et. al. (1992) used the momentum principle to determine the hydraulic effect of LWD, the effect being quantified in terms of afflux or backwater effect. If flow is subcritical (Froude number <

1), then apart from local disturbance of the velocity profile, LWD only has an influence in the upstream direction. Quantifying the backwater effects is problematical because of the practical difficulties of directly measuring the afflux at debris jams. An alternative to direct measurement is prediction on the basis of a known relationship between afflux and more easily measured parameters. Gippel et al. used the results of a laboratory hydraulic study to develop a method of determining the afflux caused by LWD (see Figure 7.1).

They propose the use of the following equation to calculate afflux :

$$\Delta h = \frac{h_3\left[\left(F^2-1\right)+\sqrt{\left(F^2-1\right)^2+3C_D BF^2}\right]}{3} \tag{7.11}$$

where, Δh = afflux = $h_1 - h_3$ (m), and the drag coefficient (C_D) is given by:

$$C_D = \frac{F_D}{\frac{1}{2}\rho U_1^2 L_* d} \tag{7.12}$$

where, F_D = drag force (N), ρ = density of water (1000 kg/m^3), U_1 = mean velocity at section upstream of object (m/s^{-1}), L_* = projected length of LWD in flow (m), d = diameter of LWD (m)

and the Froude number (F) is defined by:

$$F = \frac{U_3}{\sqrt{gh_3}} \tag{7.13}$$

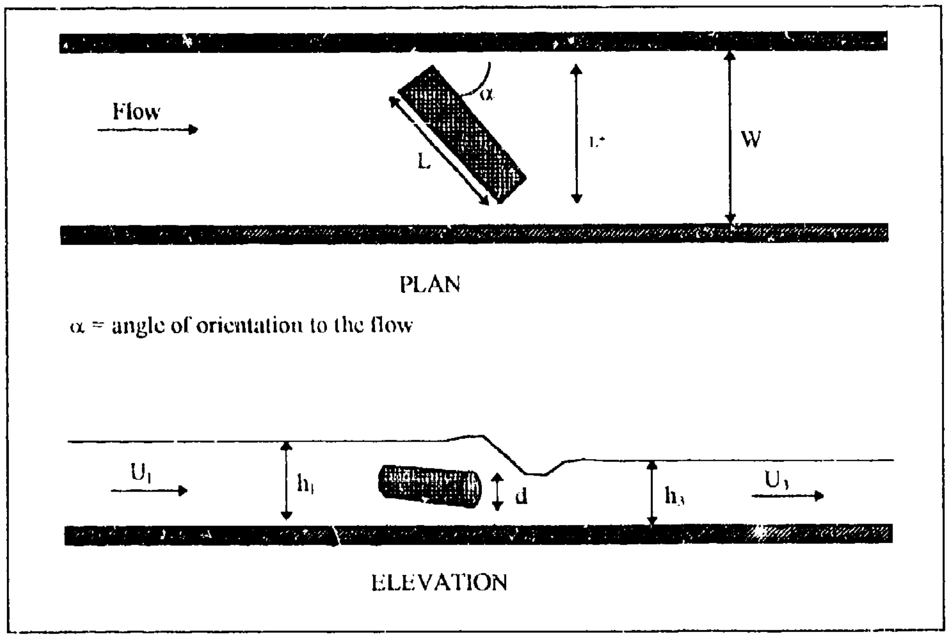
where, U_3 = mean velocity at section downstream of object (m/s^{-1}), h_3 = water depth downstream of LWD (m)

and the blockage ratio (B) is given by:

$$B = L_* d / A \tag{7.14}$$

where, $A = W.h_1$ = cross sectional area of flow (m^2)

Figure 7.1 Definition sketch of LWD model by Gippel et al. (1992)



Thus, the afflux depends on F, C_D and B. The Froude number can be calculated from direct measurement or from flow records. B can be found from a field survey. The remaining problem centres on selecting an appropriate drag coefficient. The drag characteristics of a cylinder in infinite flow are well known (Petryk and Bosmajian, 1975). Less is known about drag on cylinders within boundaries where the "blockage effect" is significant and the drag coefficient is consequently increased.

Gippel et al. conducted experiments on LWD models to determine drag force, using a towing carriage and water tunnel. Froude number, LWD length to diameter ratio and LWD depth from the bed all affected drag coefficient, but were much less important than the blockage effect, angle of orientation to the flow and the shielding effect (of one piece of LWD behind another). A suitable drag coefficient (C'_D) for the LWD in question can be selected from their experimental results (Gippel et. al 1992, figures 3.8 or 3.12) on the basis of its overall shape and angle of orientation. The drag coefficient should then be adjusted for the blockage effect, which can be calculated using the following equation developed by Gippel et. al. using their empirical data from flume studies:

$$C_D = C'_D\,(1-B)^{-3} \qquad (7.15)$$

where, C_D = adjusted drag coefficient, and C'_D = drag coefficient in infinite flow.

These data are then substituted into equation 7.11 to calculate the afflux.

Predicted and measured afflux values resulting from the flume study were very closely correlated, and they conclude that the flume conditions did not seriously violate any of the assumptions in equation 7.11. The proposed method of afflux estimation was then applied to data collected from the Thomson River, Victoria and revealed that de-snagging there would produce a reduction in stage of only 0.01m at bankfull flow. Appendix C presents the method for predicting flow afflux due to LWD, developed by Gippel et al. (1992).

In conclusion this method of backwater or afflux calculation due to individual items of LWD could be used as a tool to help determine whether the afflux reduction due to LWD removal would have a significant, positive impact according to the perceived management requirements or whether LWD could be left in place perhaps, re-orientated, lopped or even re-introduced where sympathetic rehabilitation management is desirable, without significant effect on high in-bank stages.

8 IMPACT OF LWD AT BRIDGES

8.1 Introduction

In an investigation of bridge scour research needs, Jones et. al. (1991) cited the affect of debris on pier scour depths as a subject of pressing concern that required model studies and field observations to characterise debris build-up. Doheny (1993) observed scour conditions at 876 highway bridges in Maryland and, amongst other relationships, found that bridges in forested, urban and pasture basins were more prone to blockage than those in basins with row crops or swamp. Diehl & Bryan (1993) assessed potential debris volumes that could be transported to bridge sites in the West Harpeth River basin, Tennessee and found bank instability to be the channel characteristic most useful in identifying channel reaches with high potential for production of LWD. Instability through channel migration and mass failure or fluvial erosion can be detected on maps and aerial photographs (Diehl & Bryan, 1993). A study by Parola, Fenske & Hagerty was initiated to investigated the basin-wide impact of the 1993 Mississippi River Basin flooding on damage to the highway infrastructure. Structural geometry information, as well as hydraulic information, was collected at two sites where bridges had collapsed at least partly as a result of debris loading and was noted to be a contributing factor in the lateral load and scour of many bridges. Plate 7 shows the Missouri 113 bridge over Florida Creek, where floating debris was a key factor in its collapse.

Plate 7 : Bridge 113 over Florida Creek, Skidmore Missouri. Failure due to debris loading. Source : Parola, Fenske & Hagerty (1994).

7.2 Methods for Managing Floating Debris at Bridges

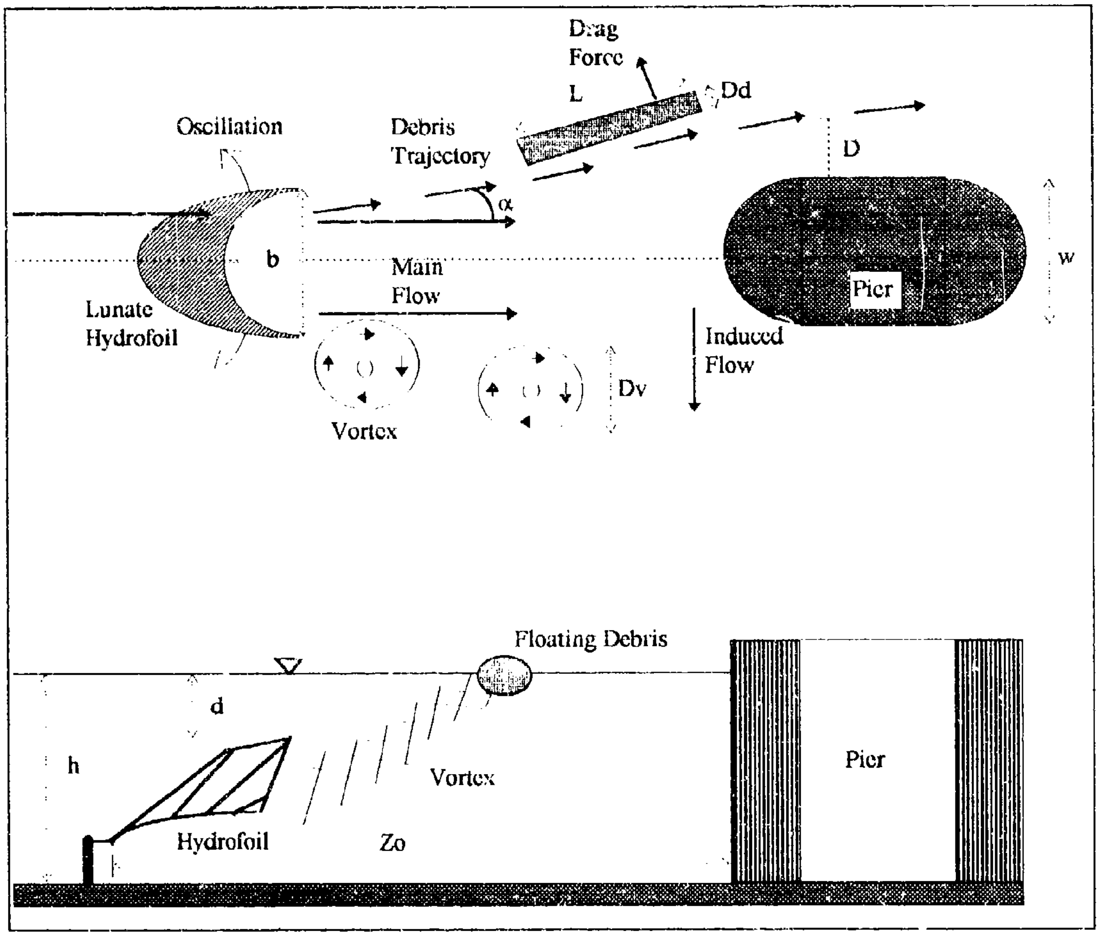
Only one paper has been found that directly addresses debris management at bridges. Saunders & Oppenheimer (1993) believe that conventional methods of protecting piers from floating debris are inadequate. They comment that the use of pilings, or some other barrier upstream of a bridge, can actually exacerbate the problem because the debris accumulated may all be released at one time in the form of a raft which cannot be pass under the bridge. They describe a novel deflector, a lunate shaped hydrofoil which generates counter-rotating streamwise vortices in its wake, positioned below the surface so that it is not impacted by debris upstream of the piers and so that the vortices migrate to the surface ahead of the pier.

The principle is that the near surface flow induced by the vortices deflects debris safely around the pier. Figure 8.1 shows the hydrofoil in elevation and planform. The foil is mounted on a tether or pylon at a depth, d, below the surface and a distance, Zo, upstream of the pier and is inclined at an angle such that the force on the foil is downwards and the reaction on the water causes a local motion upwards towards the surface. After interacting with the vortex, debris is deflected at the angle, α, and is displaced sideways by a distance, D, by the time it reaches the pier.

A flume model constructed by Saunders & Oppenheimer indicated that the vorticity remains highly concentrated for a distance of about 20 times the span of the hydrofoil, b, when b = 0.6xh (depth of flow). The problem is characterised by a bridge pier width w and by the size of the debris. An average debris size is utilised with diameter Dd and length L. The vortex produced by the device has a characteristic diameter, Dv, of order b (hydrofoil span). If Dd > Dv then the vortex will not impart a net motion to the debris, so they recommend a value of b > 2Dd or b = w (pier width) as, they assume, the majority of debris will have a diameter less than the pier width and this scaling will ensure that the vortex is positioned correctly with respect to the pier. It is also suggested that the device be tethered so that it can oscillate transversely to the flow, with the result that the vortices will tend to destabilise any debris that might have accumulated on the face of the pier.

In flume tests the hydrofoil is reported to work very effectively and the device would appear to offer a possible approach to managing floating debris at bridges. However, if the average debris length is greater than the pier spacing debris floating with their long axis transverse to the flow are still likely to be trapped and the vortices might even turn flow parallel debris through 90 degrees so it is more likely to become jammed between adjacent piers.

Figure 8.1 Hydrofoil debris deflector



8.3 DEBRIS AT BRIDGE PIER PREDICTION PROGRAM (DBP3)

A computer model has been developed to calculate the probability of debris build-up at bridge piers, and the associated debris induced scour, based upon modified theoretical equations published by Melville and Dongol (1992) and Simons and Li (1979). Version 2.0 of the model (DBP3) is also included on the enclosed disk.

There are only a limited number of studies that have addressed the problem of debris accumulations at bridges. Melville & Dongol (1992) look at the problem of pier scour due to debris, while Simons & Li (see Callander, 1980) have used a probabilistic approach to quantify the rate of bridge span blockage by debris and the subsequent backwater effect, pressure forces generated on the piers.

Local scour at bridge piers has been extensively investigated. However the impact of debris rafts at piers which create additional flow obstruction and therefore increase scour depths has been largely neglected. A design method for estimation of scour depths at piers is presented by Melville and Sutherland (1988), based on envelope curves from laboratory data. The design curve for pier scour without debris accumulations, developed by Melville and Sutherland is described by the following two equations:

$$\frac{ds}{D} = 1.872\left(\frac{Y}{D}\right)^{0.255} \qquad \left(\frac{Y}{D} < 2.6\right) \qquad (8.1)$$

$$\frac{ds}{D} = 2.4 \qquad \left(\frac{Y}{D} \geq 2.6\right) \qquad (8.2)$$

where, ds = depth of scour (m), D = bridge pier diameter(m), and Y = approach flow depth (m)

These relationships are affected, however, by additional factors where clear-water scour conditions exist, the flow is relatively shallow, and the sediment size relatively coarse. In the case of non-cylindrical piers, additional multiplying factors are applied to account for piers shape and alignment.

Scour depth due to the pier is calculated in the program using the full design method presented by Melville and Sutherland (1988) rather than the simplified version stated in equations 8.1 and 8.2. Total scour at a bridge pier is defined as

$$ds = k_I k_d k_y k_\alpha k_s D \tag{8.3}$$

where, ds = total scour depth (m), k_I = flow intensity factor, k_d = sediment size factor, k_y = flow depth factor, k_α = pier alignment factor, k_s = pier shape factor, and D = pier diameter (m).

- **Flow intensity factor (k_I)**

$$k_I = 2.4\left[\frac{U-(Ua-Uc)}{Uc}\right] \quad \text{if } \frac{U-(Ua-Uc)}{Uc} < 1 \tag{8.4}$$

$$k_I = 2.4 \quad \text{if } \frac{U-(Ua-Uc)}{Uc} > 1 \tag{8.5}$$

where, U = mean approach flow velocity (m/s^{-1}), Ua = mean approach velocity at the armour peak (m/s^{-1}), and Uc = mean approach flow velocity at threshold condition (m/s^{-1}).

$$Uc = u_{*c}\, 5.75\log\left(\frac{y}{d_{50}}\right) + 5.53u_{*c} \tag{8.6}$$

where, u_{*c} = critical shear velocity (m/s^{-1}), y = total flow depth (m), d_{50} = median particle size (m).

$$u_{*c} = \sqrt{\theta[(\rho s - \rho w)gd_{50}]} \tag{8.7}$$

where, θ = Shield's parameter/the critical shear stress (taken to be 0.05 in the program), ρ_s = density of the sediment (taken as 2650 kg/m^3 in the program), ρ_s = density of water (1000 kg/m^3), and g = gravitational acceleration (9.81 m/s^{-2})

$$Ua = 0.8\left[U_{*ca}\, 5.75\log\left(\frac{y}{d_{50a}}\right) + 5.53U_{*ca}\right] \quad \text{if } Ua \le Uc \tag{8.8}$$

$$Ua = Uc \quad \text{if } Ua > Uc \tag{8.9}$$

where, U_{*ca} = critical shear velocity of armoured bed, calculated as per equation 8.7 using d_{50a} rather than d_{50} (m/s^{-1}), d_{50a} = d_{50} size of the coarsest armour layer = d_{max} / 1.8 m), and d_{max} = maximum particle size for a nonuniform sediment (m).

• Sediment size factor (k_d)

if $\frac{U-(Ua-Uc)}{Uc} > 1$

$k_d = 1.0$ if $D/d_{50} > 25$ (8.10)

$k_d = 0.57\log\left(2.24\left[D/d_{50}\right]\right)$ if $D/d_{50} < 25$ 8.11)

if $\frac{U-(Ua-Uc)}{Uc} < 1$ and $\sigma_g < 1.3$ (where σ_g = standard deviation of the grain size distribution = d_{84} / d_{50})

Equations8.10 and 8.11 are calculated using d_{50a} (8.12)

• Flow depth factor (k_y)

$k_y = 1.0,$ if $y/D > 2.6$ (8.13)

$k_y = 0.78\left(y/D\right)^{0.255}$ if $y/D < 2.6$ (8.14)

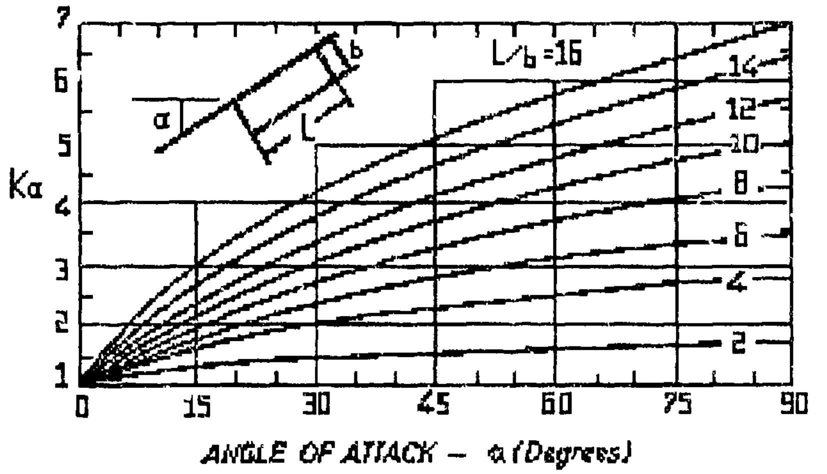
• Pier alignment factor (k_α)

This is determined using figure 8.2.

• Pier shape factor (k_s)

Pier shape factors are presented in figure 8.3. The program contains a look-up table of pier shape factor.

Figure 8.2 : Alignment Factor K_α (after Melville & Sutherland, 1988)



L= pier length; b = pier diameter

Figure 8.3 Pier Shape Factors (after Melville & Sutherland, 1988)

Shape in plan	Length/ width	Tison (1940)	Laursen and Toch (1956)	Chabert and Engeldinger (1956)	Venkatadri (1965
Circular	1.0	1.0	1.0	1.0	1.0
Lenticular	2.0	-	0.97	-	-
	3.0	-	0.76	-	-
	4.0	0.67	-	0.73	-
	7.0	0.41	-	-	-
Parabolic nose	-	-	-	-	0.56
Traingular nose, 60°	-	-	-	-	0.75
Triangular nose, 90°	-	-	-	-	1.25
Elliptic	2.0	-	0.91	-	-
	3.0	-	0.83	-	-
Ogival	4.0	-	-	0.92	-
Joukowski	4.0	-	-	0.86	-
	4.1	0.76	-	-	-
	2.0	-	1.11	-	-
Rectangular	4.0	1.40	-	1.11	-
	6.0	-	1.11	-	

Melville and Dongol (1992) present a method for determining total scour due to a bridge pier and floating debris raft, based upon flume model data. The experimental arrangement used by Melville and Dongol is shown in Figure 8.4.

The trend in equation 8.1 was found to also describe scour due to piers with debris accumulations for values of Y/D < 4. At higher values of Y/D scour depths decreased again

because the proportion of pier length covered by debris decreased. For deep flows the effect of debris became insignificant and tended towards the value ds/D =2.4.

Analysis from the model produced the following equation for bridge scour affected by a debris raft based upon an effective pier diameter (De) :

$$De = \frac{Td^{*}Dd + \left(Y - Td^{*}\right)D}{Y} \qquad (8.15)$$

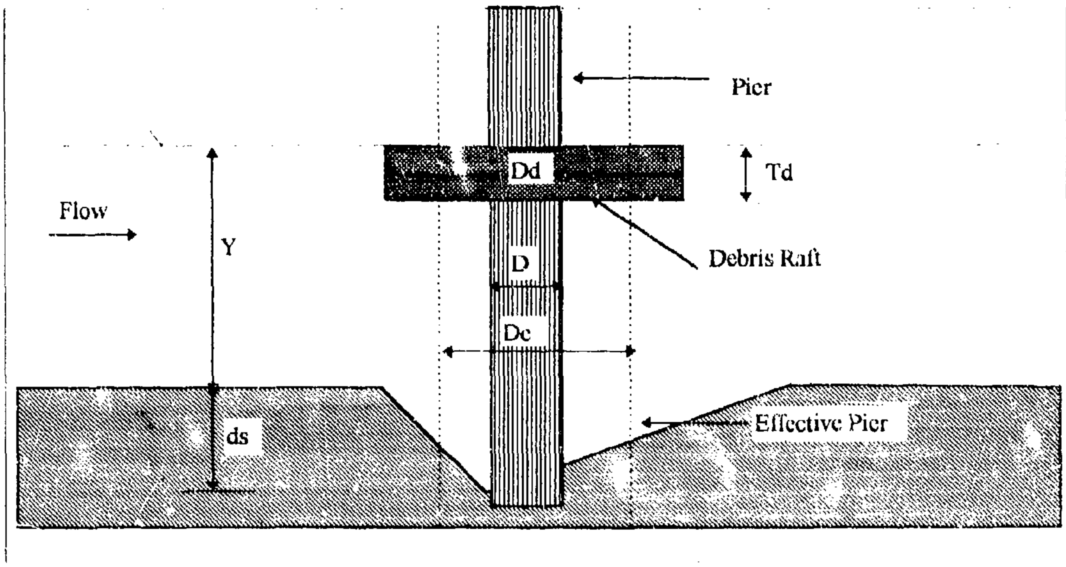
where, Td^{*} - 0.52Td, Td = debris raft depth (m), Dd = debris raft length parallel to the flow (m), Y = flow depth (m), and D = pier diameter (m).

The factor 0.52 was determined by evaluating the limits of Td and Dd/D for the hypothetical case where D is assumed to be zero and the debris is assumed to extend to the base of the scour hole.

D can therefore be substituted for De to calculate scour depth at piers with debris accumulations using the Melville and Sutherland design method. Conversely a maximum allowable Td and Dd can be calculated by specifying an upper scour depth within an acceptable factor of safety for a given pier size.

Consideration of the likelihood of debris build-up is not addressed by Melville and Dongol (1992) but they do note, however, that single cylindrical piers are the least likely shape to accumulate debris, and that the free space between columns is seldom great enough to pass debris. Prediction of the size of possible debris rafts accumulations remains the biggest problem for accurate factor of safety calculations.

Figure 8.4 Experimental Set-up (after Melville and Dongol, 1992)



8.3.1 Probability based debris build-up model

The rate of debris accumulation at a bridge is difficult to quantify. The only method found in the literature is that presented by Simons & Li (1979) in an MSc thesis by Callander (1980) entitled "Fluvial processes occurring at bridge sites".

According to Simons & Li, the trapping efficiency of a bridge is determined by:

1) Clearance beneath the bridge

2) Span lengths

3) Size and concentration of debris elements

The following possible consequences are identified which can result from debris blockage:

1) Backwater effects

2) Potential local flow diversion

3) Channel avulsion

4) Bridge failure

Simons & Li express the volume of debris as a fraction of the sediment yield (mass), and suggest a vegetation debris yield of 1%. In an attempt to estimate the number and volume of trees arriving at a bridge they utilise [illegible] volume of floodplain erosion necessary to yield a tree, and use a representative tree size. For [illegible]

Trees are assumed to be cylindrical, with a diameter Dt and a height Ht. The span between piers is, Ls and the clearance between the water surface and the underside of the bridge is C. The chance that a tree will be trapped depends on a larger diameter however, Db, which represents either the canopy dimension or the root zone, whichever is greater (see figure 8.5). If Ht > Ls the probability of at least one average tree being trapped is 100%. The blocked area is then estimated to be, NHtDt, where N is the equivalent number of average trees assumed to be trapped against the upstream face of the bridge. If Ht < Ls a probabilistic approach is used. Pt is the probability of a tree being trapped and as the blockage beneath a span increases the chance of other trees being trapped increases. The probability of the first tree being trapped is assumed to be a ratio of half the tree diameter, Db, to the total waterway area beneath a span, LsC. Hence:

$$PT1 = \frac{\frac{1}{2}(\pi Db^2 / 4)}{LsC} = \frac{\pi}{8}\frac{Db^2}{LsC} \tag{8.16}$$

where, PT1 = probability of the first tree becoming trapped, Db = canopy/root wad diameter (m), Ls = distance between piers (m), C = distance between water surface and the underside of the bridge (m), and $\pi = 3.14$.

Li (see Callander, 1980) observed that a tree caught on a pier will in general lie with its trunk in the direction of flow. A tree thus trapped offers an area of

$$\tfrac{1}{2}(\pi Db^2 / 4) = \pi / 8 Db^2 \tag{8.17}$$

to trap further debris.

In general when (m-1) trees are trapped beneath a span the probability of an mth tree becoming trapped (PTm) is:

$$PTm = \frac{\pi Db^2 / 8}{LsC - (m-1)(\pi Db^2 / 8)} \tag{8.18}$$

The probability of passing all NT trees from the watershed is:

$$(1\text{-}PT1)^{NT} \qquad (8.19)$$

The probability of at least one tree being trapped at a span(P1) is:

$$P1 = 1-(1-PT1)^{N} \qquad (8.20)$$

where, N is the equivalent number of average trees arriving at the span. According to Li most trees will stay close to the bank, thus:

$$N = NT / 2 \qquad (8.21)$$

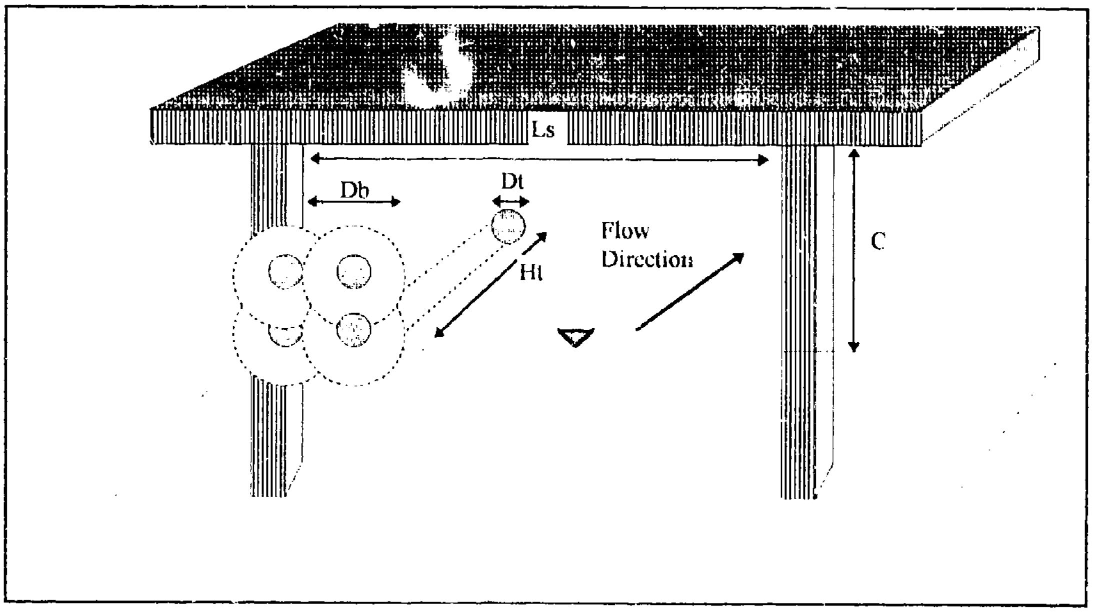
The probability that m trees will be trapped (Pm) is:

$$Pm = [1-(1-PTm)^{[N-(m-1)]}]P(m-1) \qquad (8.22)$$

On this basis the probability of a least m trees being trapped (for any m < N) can be estimated. To calculate Td and Dd requires an estimate of the blockage area. It is assumed that debris elements stack up and that trees overlap by Db/2. Thus for m trees trapped the percentage of the waterway area which is blocked is:

$$\%Blockage = \frac{m(\frac{1}{2}\pi\, Db^2/4)}{LsC} \times 100\% \qquad (8.23)$$

Figure 8.5 Schematic diagram of debris accumulation at bridge piers



8.3.2 Program Construction and Input Variables

The program applies the Simons and Li probability model and then calculates the potential pier scour due to the predicted debris mat size based on the blockage area and assuming all the trees available in the reach upstream become trapped beneath a span.

Initially average (mid-height) tree trunk diameter (Dt), a maximum tree diameter (Db), (either root wad or canopy, whichever is the larger), and average tree height (Ht) values are entered. Next, the number of trees approaching the bridge span (NT) is entered. Although Simons and Li suggest using N = NT/2 in the probability calculations, the model assumes that all the trees available in the upstream reach will pass through the span in question. However, the number of spans (S) between piers (P) that are set in the channel will normally be S = P + 1 (counting the two spans between pier and river bank). It is therefore necessary, for an accurate assessment of blockage potential and debris related scour, to calculate probabilities for each span individually, perhaps using a simple division rule (N = NT / S) for N trees arriving at each span. It is left up to the user to make the appropriate adjustments for each span. NT can either be estimated in the field and entered as a total potential tree supply or it can be estimated through calculation of potential bank failure in the upstream reach. To calculate the latter estimate requires knowledge of riparian tree density, the length of the reach in question and the potential bank failure width. The failure width value can be determined using an appropriate bank stability

model such as BURBANK (developed under the DEC Monitoring Project). The potential number of trees that will reach the span is then calculated as:

NT = tree density x failure width x reach length x 2 (two banks) (8.24)

Finally, the bridge pier diameter (D), span between piers (ls) and average flow depth (Y) values are entered.

Calculations in the model then proceed as follows:

1) If tree height is less than the pier spacing the probability of the first tree becoming caught is calculated, followed by the probability of the next tree becoming caught, consecutively. This is repeated for n trees up to NT.

In the calculation of trapping potential it is considered that, the use of the ratio of tree area to the entire area under the span as suggested by Simons and Li, is somewhat inappropriate as tree capture is dependent only upon the length of span and diameter of tree given that the water level is constant. Deck elevation above the water (C) has, therefore, been substituted by maximum tree diameter (Db) in this model.

2) If tree height is greater than span width it is assumed, as outlined in the Simons and Li model, that at least one tree will become trapped and thus all subsequent trees arriving at the span will also be caught.

3) The percentage of the channel cross-sectional area that is blocked if all the trees supplied to the reach become trapped is calculated, as outlined in the theoretical model (see figure 8.5) for Ht < ls. However if Ht > ls, Dt is substituted for Db and the blockage area is calculated as:

square root x blockage area = blockage depth (assuming debris builds up as a square) x tree height / span width x flow depth x 100 % (8.25)

This calculation assumes that for Ht > ls all trees will build up in a square raft, when view orthogonal to the flow, as oppose to parallel with the flow when Ht < ls.

4) The hydrostatic pressure force on each pier per unit width is calculated as :

pressure force = bulk weight of water x

blockage depth x 1 (unit width) x (blockage depth / 2). (8.26)

5) Dynamic pressure force on the pier is calculated using the following equation:

$$F_d = 0.5\ \rho_w\ U^2\ A\ C_D / 1000 \qquad (8.27)$$

where, F_d = Force on pier (kN), ρ_w = density of water (1000 kg/m^3), U = approach flow velocity (m/s^{-1}), A = frontal area of debris raft normal to the flow (m^2), and C_D = drag coefficient of debris raft. A estimated value of C_D = 1.5 is used in the program.

6) Bridge pier scour with the debris accumulation is then calculated using the Melville and Dongol model. If Ht > ls the debris raft depth is taken as the square root of the blockage area (assuming debris build-up is in a square). If Ht < ls, debris raft diameter is assumed to be Ht because the debris is aligned parallel with the direction of flow. Factors (K_I), (K_y), (K_d) and (K_s) are incorporated into the model. The program requires the following data to calculate these factors: mean approach velocity for the design flood (U); median particle size (d_{50}); the largest particle size (d_{max}); standard deviation of the particle distribution (σ_g) = d_{84}/d_{50}; pier diameter (D); angle of flow attack; pier dimensions; and pier shape. The alignment factor, K_α, must be determined by the user using figure 8.2.

It should be noted that the formula developed by Melville and Dongol for calculating debris related pier scour was only developed for floating debris accumulations. However, it is considered that this formula can be extended to debris accumulations which have their base resting on the channel bed, as the critical factor in the calculation method is an effective pier diameter which is, in any case, extended to the channel bed in the situation where the debris is floating.

8.3.3 Testing the Model

The pier scour component of this model has been tested using field data collected from a number of bridges in the survey reaches in northern Mississippi. Scour depths were measured at each site (during low flow conditions) on piers which had significant debris accumulations. Plate 8 shows debris build-up against the piers of a county road bridge over Fannegusha Creek. The parameters required for the model calculations were also collected. Bankfull discharge and channel dimension values obtained from Watson et al. (1993) were used in the model to

simulate critical conditions because accurate discharge measurements could not be made at the time of the survey. Logistical constraints also prevented the calculation of realistic upstream debris loadings that could arrive at each pier and so these were represented by the dimensions of the debris accumulations actually present at the time of survey. Table 8.1 shows a summary of the surveyed scour values and the model results. Figure 8.6 shows a plot of these results. The diagonal line in this plot represents a perfect match between the actual measured scour depths and those predicted by the model. The graph shows how debris rafts increase scour by a factor of 2 to 4. It is evident that the model significantly overestimates scour due to both the pier and debris raft and slightly overestimates scour due to the pier alone. The predicted results would, therefore, appear to be rather conservative, although this does create a good factor of safety.

The discrepancy between measured and predicted values may be explained by the fact that scour hole depths are much greater under bankfull flow conditions, than those at low flow (when the measurements were made) due to general scour but are subsequently reduced as flows recede owing to the deposition of the highly mobile sand and silt sediment load. To fully validate the model it will therefore be necessary to undertake further fieldwork to measure the necessary parameters, including scour depth values during bankfull flow conditions. The model must also be validated using different channel environments such as armoured, gravel-bed rivers.

Table 8.1 Pier scour summary table

Creek	Predicted pier scour (m)	Predicted pier & debris scour (m)	Measured scour (m)
Abiaca 3	1.33	1.44	0.3
Harland 1	1.32	1.55	0.48
Abiaca 6	0.83	2.46	0.61
Fannegusha	0.72	3.12	0
sykes	0.72	4.31	1
Redbanks	1.28	2.98	0.5
Burney Branch	0.80	2.07	0.43

Figure 8.6 Relationship between Measured and Predicted Pier Scour Depths

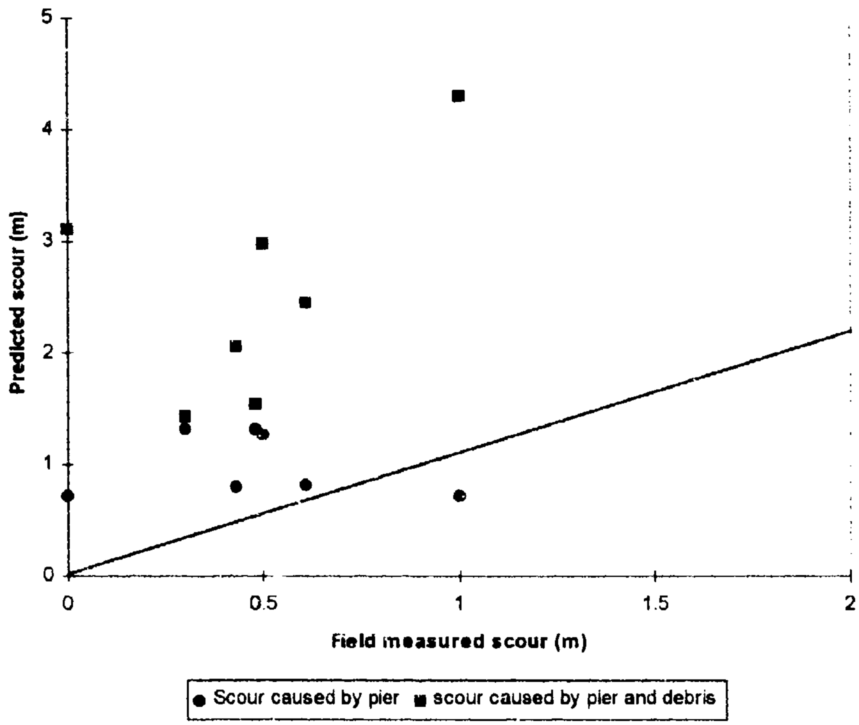


Plate 8 Debris build-up against the piers of a county road bridge over Fannegusha Creek

9 CONCLUSIONS

The following conclusions can be drawn from the data and results presented in this paper about the impact of LWD in degrading, sand-bed, rivers:

- The main debris input mechanisms (outer bank erosion in bends and bank mass-wasting in degrading reaches) are spatially predictable processes which can be used to predict and map the distribution of major debris sources in the watershed.
- Stream power per unit bed area was found to be a statistically significant predictor of debris volume. However, watershed area was found not to be a good predictor of debris volumes and jam frequency, probably because the channels surveyed are undergoing degradational cycles which disrupt simple hydraulic geometry relationships.
- Observed differences in the volume of debris and frequency of jams in each Stage of the Schumm (1984) Channel Evolution Model (CEM) can be explained by the suite of processes which occur in the CEM evolution sequence.
- The conceptual jam classification model (Underflow, Dam, Deflector, Flow Parallel) shown schematically in Figure 5.2 has been found to predict with reasonable accuracy the observed distribution of jam types encountered when moving downstream through the drainage network, despite distortion of the simple underlying relationship in the model (ratio of average channel width to 'key' debris length) by channel evolution processes.
- Jam-induced sedimentation and scour values have been found to have statistically significant trends when correlated with watershed area. These trends can be explained because they correspond to the changing flow processes and consequent scour and sedimentation patterns, induced by each jam type encountered through the watershed. Underflow jams, in small watersheds, interfere very little with the flow and therefore do not have a high scour and sediment retention potential. Dam type jams, found further downstream, cause large volumes of sediment to be stored in backwaters, but also cause plunge pool scour. Downstream from Dam type jams at Deflector jams, sediment is stored in the lee of jams as bar deposits, but the jams also cause flow to impinge on one or both banks, resulting in localised scour and bank collapse. Further downstream still, Flow-Parallel debris block the flow much less so that energy dissipation and, therefore, sediment retention and scour are less significant.
- The net sediment balance results shown in Table 5.2 support the arguments that debris helps to accelerate sedimentation processes in these highly unstable channels and that jams may even act as temporary grade control structures. LWD therefore accelerates channel equilibrating

processes in stages 4 and 5 of the Schumm et al. (1984) Channel Evolution Model. Jams should not, therefore, be removed unless they threaten structures and addition of LWD is recommended to aid sediment retention and improve aquatic habitat in debris-starved degrading reaches.

- Meaningful conclusions concerning short-term jam stability can only be made when the survey data is compared with corresponding discharge data for the one year interval, which will show the magnitude and frequency of events that the jams were able to survive. The relevant data are not available, as yet, to permit this analysis. Given the warm, humid climate, and highly erodible nature of these channels it is likely, however, that jams are more transient features in North Mississippi than, for example, in the Pacific North West because debris will decompose more quickly and become bypassed by bank erosion and bed scour. A long-term monitoring programme is required, however, to verify this assertion.
- Four LWD analysis models are presented in this work which have been tested and verified using field data and are recommended for channel design and management. They are:

1) The Shields & Smith (1992) LWD flow resistance model.

This model predicts Darcy-Weisbach friction factor due to LWD jam accumulations. It has a sound theoretical basis and has shown a reasonable correlation between measured and computed friction factors.

2) The Gippel et al. (1992) LWD induced flow afflux model.

This analysis method has been developed from flume experiments and theoretical hydraulic considerations. The analysis method is presented in a manual format in Appendix C. This method of backwater or afflux calculation due to individual items of LWD can be used as a tool to help determine whether the afflux reduction due to LWD removal would have a significant, positive impact according to the perceived management requirements or whether LWD could be left in place perhaps, re-orientated, lopped or even re-introduced where sympathetic rehabilitation management is desirable, without significant effect on high in-bank stages.

3) The Debris Management Program (DMP).

This computer model, presented on the disk enclosed, is designed as a management tool for predicting the geomorphic impact of LWD on channel processes and morphology throughout the

watershed. The model has been developed, tested and modified using empirical analysis of field data gathered from 23 river reaches in Northern Mississippi which are undergoing channel adjustment caused by base level change. This tool is recommended for geomorphic analysis and management of LWD in channel environments similar to those from which the model has been developed.

4) The Debris at Bridge Pier Prediction Program (DBP3).

This computer model, also included on the enclosed disk, determines the probability of debris build up at bridge piers, the consequent maximum debris enhanced potential pier scour and the change in hydrostatic and dynamic pressure forces on the pier. The model is developed from research presented by Melville and Sutherland (1988), Melville and Dongol (1992) and Simons and Li (see Callander, 1980). The model has been tested using field data collected from a number of bridges in Northern Mississippi and demonstrates that the empirical and theoretical assumptions of the model provide a good factor of safety for bridge pier design analysis where LWD build-up is a potential hazard.

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APPENDIX A

LWD MAMAGEMENT PROGRAM GIS DATA INPUT SYSTEM

1.1 Introduction

This GIS (Geographical Information System) user interface demonstrates how a GIS (ARC/INFO) can be used in conjunction with external programming to assist in management practices associated with erosion control.

The GIS is used to calculate variables of sediment type, land use, and sub-watershed are which are the input variables for the DMP. The GIS has been constructed for the Abiaca Creek watershed, located within the DEC study area in Northern Mississippi. The operation of the program is set up to facilitate interactive selection of stream sections within the watershed. The soil type and landuse variables are calculated by combining polygon coverage's and overlaying them onto the stream network. The watershed area is calculated through the use of a digital elevation model, which is also used to derive the stream network. The system macro language (AML) of the GIS is used to automate data input in the DMP. A pull down menu is employed to create a user friendly windows style environment which guides the user through the steps necessary to obtain management information.

1.2 Installation

The GIS is in UNIX ARC/INFO format, and is contained in a directory named "Project"

The program can be obtained upon request from **nick@geography.nottingham.ac.uk** and will be sent via FTP or on DAT tape. "Project" requires about 98 MB of hard drive space to install.

The "Project" directory should be copied into the same directory as ARC if ARC is not in the command path.

To run the GIS load ARC. At the ARC: prompt type **&RUN Project** to activate the AML (ARC Macro Language) driven user interface.

1.3 Methodology

A fundamental requirement for this utility was too extract these variables automatically with limited user interaction and run the DMP, all within the framework of the GIS

Figure 1.1 outlines the method of approach from variable extraction to the final output from the DMP.

The section of stream which the user is querying is interactively selected by using the screen cursor operated by the mouse. This provides the co-ordinates for the analysis from other data layers which are all geometrically aligned. ARC/INFO provides interactive selection facilities which enable the user to select points on the display screen. The stream network coverage contains attribute information detailing the soil types and landuse for each arc section of stream. The original stream coverage data contained no attribute information relevant to the study. A function command called IDENTITY enables arcs (lines) to be overlaid onto polygon coverages and relate the attributes from the polygon coverage to the arcs coverage, where the arcs overlay and intersect the polygons. By converting the grid layers, soil types and landuse to polygon coverages this IDENTITY command is then used to attach the attribute information from these two data layers to the stream network. ARC/INFO facilitates conversions from raster to vector, and the GRIDPOLY command is used to convert the two raster files. Using the IDENTITY command the stream network can be overlain onto the soil polygon coverage, then the resulting new stream network coverage with soil attributes is overlain onto the landuse polygon coverage resulting in a stream coverage which has attached soil type and landuse attributes. The methodology of this process is summarised in figure 1.2.

An important requirement for the success of this project is that the stream network is geometrically true to the elevation grid for the calculation of the watershed area upstream of the query point. The interaction with the stream network is the sole method of producing a co-ordinate reference point, which is used as the starting point or watershed pour point for the area calculation from the DEM. However, the likelihood that every section of the original vector scanned stream coverage being a precise match to the DEM is small. If it does not match precisely the analysis method would failure because the watershed area calculated would be incorrect. For this reason the stream network is produced from the DEM, and converted to a vector coverage through the command GRIDLINE. The same procedure is used to produce a stream coverage with soil and landuse attributes.

Figure 1.1 Flow diagram of GIS operation

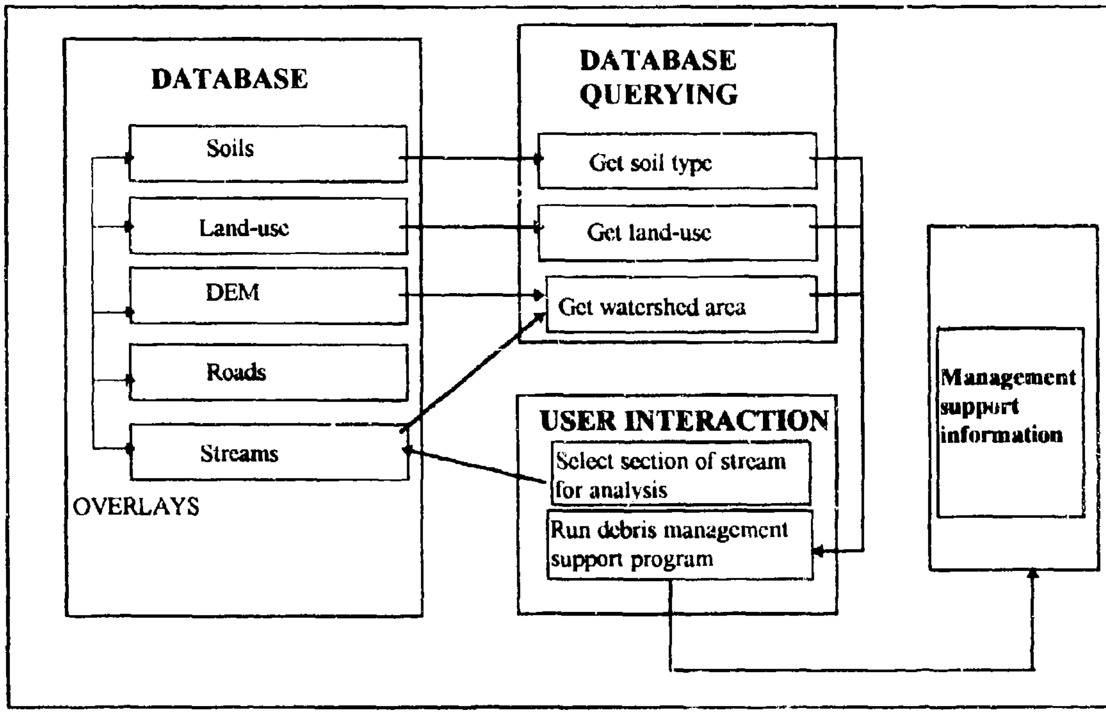
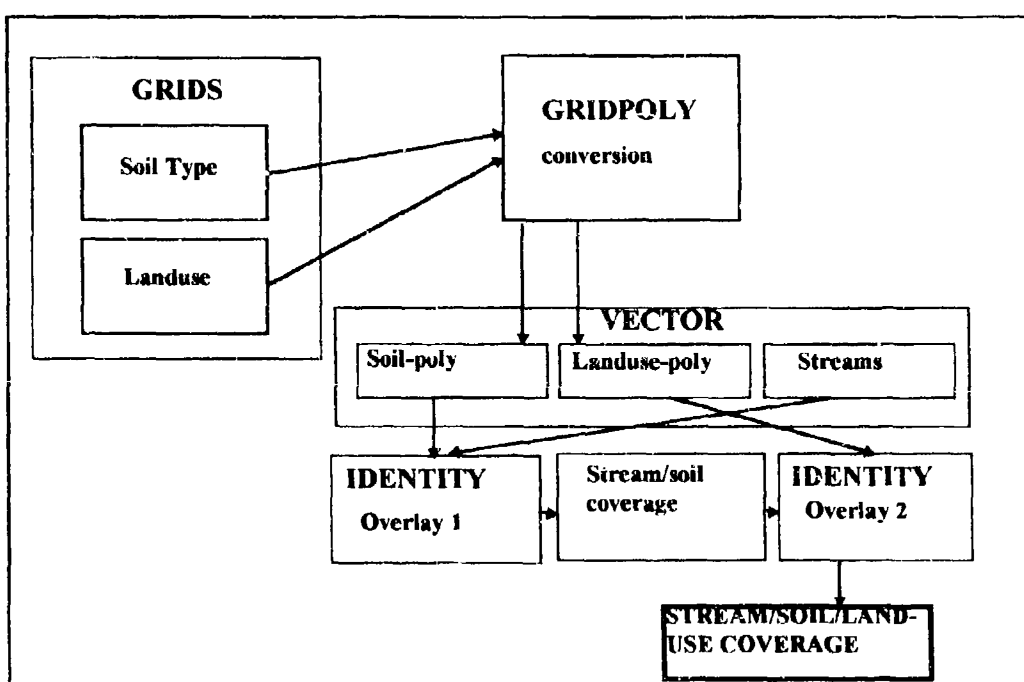


Figure 1.2 Method of producing stream coverage with soil type and landuse attributes



1.3.1 The Digital Terrain Model

A common problem in using DEM matrices for detecting linear features such as stream networks is that of depressions (sinks) in the digital surface caused by noise. The noise may result from short range variations on the digital land surface or as a result of the quantitization of the original data. Ridges and drainage courses may be missed because the grid is too coarse. ARC/INFO can detect these sinks and fill them. A sink is defined as a cell whose elevation is less than or equal to that of its eight neighbours when passing a kernel of 3x3 cells over the elevation grid (Marks 1984). ARC/INFO uses Marks method to detect these sinks and by setting a minimum elevation, which in this case was 83ft, these sinks can be filled up to that minimum height. The command FILL was used with the options of SINKS and a z value set at 83. From here the depressionless DEM was used to create matrices necessary for further analyses. The command FLOWDIRECTION creates a flow direction matrix from the DEM, which is achieved by computing the local gradient and aspect for every cell. This flow matrix is used to determine the boundary of catchment or selected sub-catchment. To find the stream network from the DEM a flow accumulation grid needs to be produced. The method behind this is an algorithm for which each cell, compares its altitude with its eight neighbours within a 3x3 kernel. The lowest neighbour is flagged, and the amount of water (which is expressed as a function of the number of cells traversed and the area of the cell) is carried over to that cell. The kernel is moved to the lowest neighbour, and the process is repeated. The ARC command that is used to carry out this process is FLOWACCUMULATION. A stream network can then be delineated using the output from this flowaccumulation grid. Flow accumulation in its simplest form is the number of up slope cells that flow into each cell. By applying a threshold value to the results of this FLOWACCUMULATION using a grid algebraic expression, a stream network can be defined. An expression was used to create a grid where the value 1 represented a stream network on a background of no data, the expression was:

stream network = con (flowaccumulation > 100, 1)

This assigns the value 1 to all cells with more than 100 cells flowing into them, and all other cells are assigned no data. A final process that was carried out, was to apply Strahler's method of stream ordering, achieved through the use of the command ORDER. The reason for creating this grid was to create a visual guide to the user, the network is colour coded, white representing a stream order of 1, while bright pink was a stream order of 6.

Once the necessary data had been constructed in the database a set of Arc Macro Language (AML) statements was used to extract the variables necessary for input into the DMSP. A command named RESELECT enables the user to interactively select a point on the stream network displayed on the screen. This function then selects all the attributes associated with that one arc which has been selected. These attributes are stored in a named INFO file (TRY) created by the RESELECT function. The next step is to calculate the upstream watershed area from that selected point. ARC/INFO command WATERSHED allows interactive selection of a pour point from the screen. By selecting at the same point as before (the RESELECT function leaves a small box on the screen marking the previous selection point, the user then selects the point again), the WATERSHED function creates a new file which represents the sub-watershed only. The count attribute in the new sub-watershed file represents the number of grid squares which make up the area of the sub-watershed. In the ARC module TABLES, new items can be created for this file, then using the CALCULATE function within TABLES a data value is assigned to represent the number of squares (one grid square = 0.000036 miles^2). Two files are therefore created in the analysis, one containing the values representing the soil type and landuse at the selected point on a stream, and one file containing the upstream watershed area from that point.

In TABLES using the function UNLOAD the relevant items from these files are selected and put into a text file which list the landuse, watershed area and soil-type respectively. This text file is the input file into the Debris Management Program.

At the arc prompt the function TASK activates a program outside the ARC/INFO environment. This TASK command is used to execute the Debris Management Program which imports the text file containing the input variables. The DMP creates an output text file which details the soil type, landuse and stream width (calculated from the watershed area) and the form of management which should take place at that section of the stream network in the Abiaca Watershed.

1.3.2 The Menu Driven Interface.

The final part to the method for this project was to tie all the data layers and interactive analyses functions together in a menu driven interface. The type of menu chosen was the pulldown version which is perhaps the most familiar to Personal Computer users. An ARC/INFO menu file is a text file, created in the operating systems text editor. The format of the menu determines how the menu is to be displayed and which choices are to be included, and what action is taken when a selection is made. Table 1.1 shows the format for this menu

file with explanatory text written in red. The AML files are described is section 1.4. Figure 1.3 shows a schematic diagram of the outlining operation of the menu interface and how it links with the GIS database.

Table 1.1 Menu Interface Commands

Draw	**main menu choice, with sub menu choices below**	
Landuse	&R LAND	** runs the AML land (displays landuse)**
Soils	&R SOILS	** runs the AML soils (displays soils)**
Streams	&R STREAMS	** runs the AML streams (displays streams)**
Roads	&R ROADS	** runs the AML roads (displays roads)**

List Attribute	**main menu choice, with sub menu choices below**	
Landuse	LIST AB-LAND-GRID.VAT	**lists attribute file**
Soils	LIST AB-SOIL-GRID.VAT	**lists attribute file**
Streams	LIST FINAL-NET.AAT	**lists attribute file**
Check Count	LIST TEST.VAT	**lists attribute file**
Soil & Landuse	LIST TRY	**lists attribute file**

Analysis	**menu choice, with sub menu choices below**	
Help	&POPUP ANL-HELP.TXT	**displays help text file**
Zoom	&R ZOOM.AML	**runs the AML zoom**
Calculate Variables	&R del.AML	**runs the AML del**

Run Program	**main menu choice, with sub menu choices below**	
Run	*R FILE.AML	**runs the AML file**

Clear	**main menu choice which clears current display**

Quit	&RETURN	**quits the menu display**

Draw: provides a list of coverages to be drawn on the screen.

List Attributes: provides a list of coverages form which the attributes associated with them can be chosen.

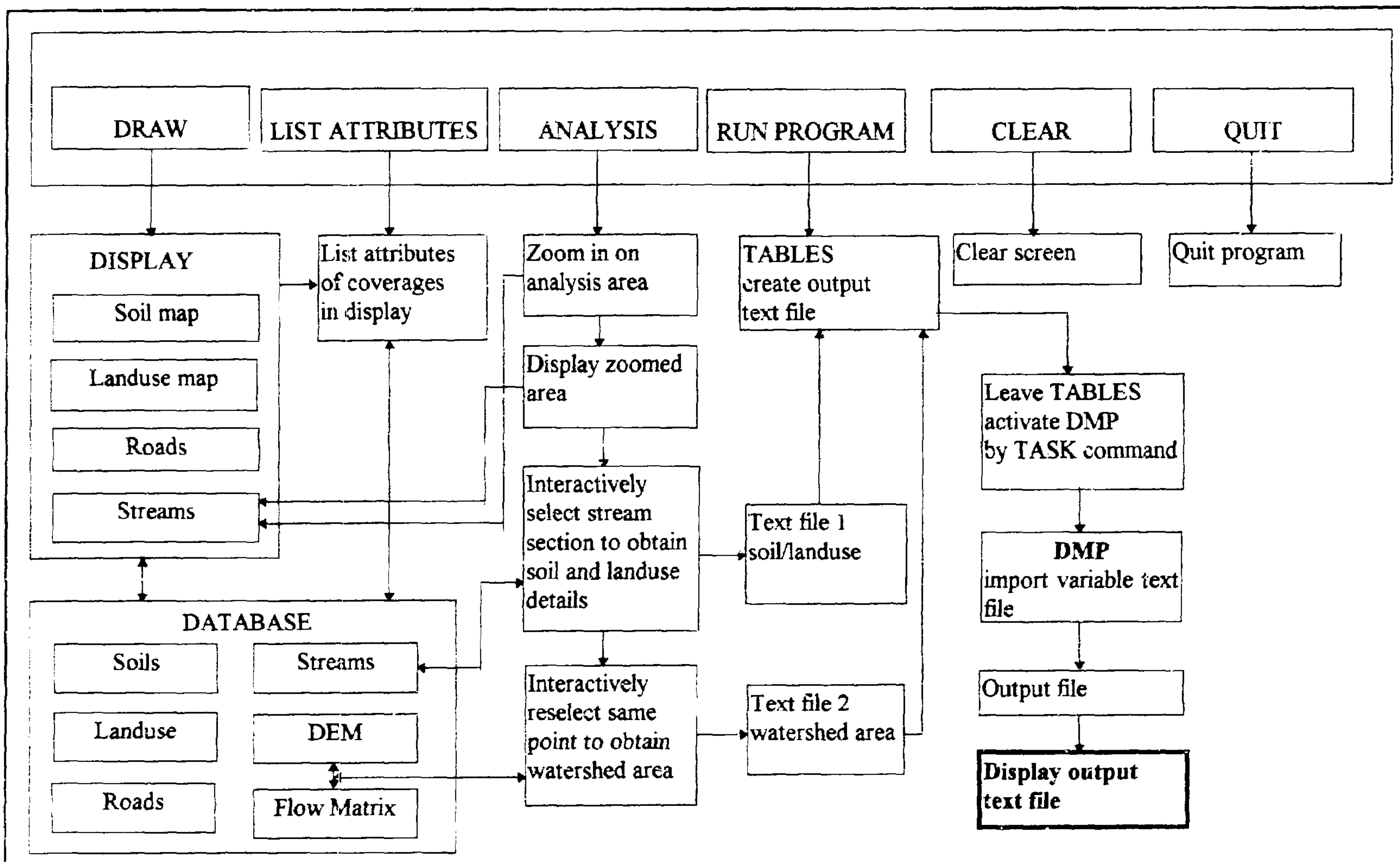
Analysis: activates the stream analysis section of the project, provides a series of help menus to guide the user through the process.

Run Program: after the stream variables have been collected the DMSP can be activated.

Clear: clear the current display on the screen.

Quit: Quits the menu and returns to the arc prompt.

Figure 1.3 Schematic of menu operation



The menus is set up in such a way that choosing a subject activates an AML program. This is set-up so that the user need not be aware of the processing that is taking place when they make a choice. The AML programs are a list of on line commands which activate various ARC/INFO functions. These AMLs could all be accomplished by typing in the numerous commands line by line. Instead an ARC/INFO function &WATCH was used to record all line entries made. This creates a watch file which contains all the commands entered at that time, these watch files are then converted to AML through the command CWTA (convert watch file to AML). By setting up watch files whilst doing the individual process by line entry, separate small command files were created which would carry out a whole process just by activating the particular AML program file in question. These AML files are then brought together through the menu interface.

1.4 AML Commands

Listed below are some of the key ARC/INFO commands used in the project with brief descriptions of their function.

IDENTITY:	computes the geometric intersection of two coverages. All features of the input coverage, as well as those features of the identity coverage that overlap the input coverage, are preserved in the output coverage.
RESELECT:	selects a set of records from the specified object i.e. arc attributes.
SINK:	creates a grid identifying all sinks, or areas of internal drainage.
FILL:	fills sinks to the value of the lowest boundary cell in the watershed.
FLOWACCUMULATION:	creates a grid of accumulated flow to each cell, by accumulating the weight for all cells that flow into each downslope cell.
FLOWDIRECTION:	creates a grid of flow direction from each cell to its steepest downslope neighbour.
WATERSHED:	creates a grid of the upslope area contributing flow to a given location.
STREAMORDER:	creates a grid of streams characterising the stream network based upon their number of tributaries.

HILLSHADE: creates a shade relief grid from a grid by considering the illumination angle and shadows.

GRIDPOLY: converts a grid to a polygon coverage. Polygons are built from groups of contiguous cells having the same cell value.

1.4.1 Arc Macro Language Programs

Programs 1 to 4 are display functions

```
1.**land**
clear
mape ab-land-grid          **sets the map extent to the landuse grid file**
map land.map               **displays a map file which has title and key**
map end                    **closes map file**
&return

2. **soil**
clear
mape ab-soil-grid
map soil.map
map end
&return

3. **streams**
mape ab-soil-grid
arcs final-net             **displays arcs coverage**
&return

4.**roads**
mape ab-soil-grid
arcs ab-roads
&return
```

Programs 5 to 9 are data handling functions

```
5.**del.aml**
&if [exists TRY -INFO] &then        **this is an if-then type statement program
&do                                 IF an INFO file called TRY exists delete it,
&sv delstat = [DELETE TRY -INFO]         if not (ELSE) continue and run
analysis.aml**
&TYPE TRY FILE DELETED
&end
&else
&r analysis.aml
&return
&ranalysis
```

6.**file.aml*8

```
q
tables                                  **this opens up the module TABLES**
additem test.vat area 14 16 n3          **creates new item AREA in the file
test.vat**
select try                              **selects INFO file try**
unload dump.txt land-code               **creates text file fump.txt inputs
land-code**
select test.vat                         **selects INFO file test.vat**
calculate area= count *0.00036          **calculates area value**
unload dump.txt area                    **inputs area into dump.txt**
q stop                                  **quits Tables**
&sv x = [task 3res 'file =0']           **activates DMSP**
&popup output.txt                       **displays the output file from the DMSP**
&stop
```

7.**zoom.aml**

```
&POPUP ZOOM-HELP.TXT                    **zooms in on analysis section of streams
mape ab-order                           the * indicates this is a user interaction**
mape*
clear
gridshades ab-order
&RETURN
```

8.**project.aml**

```
&terminal 9999                          **this is the starting AML which sets up the
rm dump.txt                             display environment in ARC/INFO deletes
rm output.txt                           previous text files and then activates the menu
&Fullscreen &Popup                      file first.menu**
display 9999 3 position 11 screen11
DISPLAY POSITION LR
grid
mape ab-land-grid
&Menu first.menu &PULLDOWN & position &ul &screen  &ul &size &frame 700 75
& STRIPE 'Stream Erosion Management System'
```

9.**analysis.aml**

```
&POPUP ANALYSIS.TXT
CLEARSELECT
SEARCHTOLERANCE 150
RESELECT FINAL-NET ARCS ONE*
INFOFILE FINAL-NET ARCS TRY SOIL-CODE TYPE LAND-CODE LAND-TYPE
LIST TRY
&POPUP SHED.TXT
KILL TEST ALL
TEST = WATERSHED (ab-net-flow, SELECTPOINT (ab-elevation,*))
LIST TEST.VAT
&POPUP CHECK.TXT
clearselect
```

```
clear
MAPE ab-order
SEARCHTOLERANCE AUTOMATIC
&RETURN
```

1.5 Data Source

The original DEC Project data resides on an Intergraph 6080 workstation, and access to the database is made with Intergraph GIS software. The purpose of the engineering database/GIS is to serve as a repository for all design, analysis, and monitoring data collected on the DEC Project. It is still in a development stage but when completed it is anticipated that the database will contain design data for all project features such as low and high-drop structures, bank stabilisation structures, floodwater retarding structures, channel improvements, levees, riser pipes, and box culverts. This design data will be complemented with date coverages suitable for various hydrological analyses such as DEMS's and soil type data.

The database contains 1:24000 digitally scanned USGS quadrangle maps and DEM's for all the DEC Project watersheds All major tributaries and highways, which have been obtained from 1:100000 USGS Digital Line Graph (DLG) files are incorporated into the database in vector format, these maps were again digitally scanned rather than digitised. Spot-view satellite photography has been incorporated into the database and is used as a visual reference for all DEC Project features. Landuse and soil type data for the DEC watersheds are incorporated in the database on a 1-acre grid. Elevation data is present on a 100ft grid.

The data that were made available for this project were the elevation, landuse and soil type grids, which were in Geographical Resource Analysis Support System (GRASS) format. The vector files were visual files only and had no specific attributes attached to them. The watershed chosen for this study was the Abiaca Creek Watershed which is one of the fifteen watersheds within the DEC Project. It was chosen because a large number of field investigation sites were located in this watershed, enabling the model to be tested against ground data.

To import the GRASS files into ARC/INFO the image (GRASS) file is converted to GRID format by initialising the command IMAGEGRID, which is one of ARC/INFO's raster conversion programs. The IGDS files were translated into ARC/INFO coverages with the IGDSARC command. Before the IGDSARC command was implemented the command IGDSINFO was used which provided a summary of what the IGDS file contains. IGDS files can be multi-layered coverages and it is therefore necessary to identify the specific layers

contained in the file for conversion. IGDSINFO provided a breakdown of the total number of elements, the names of the elements and how many of each, plus a breakdown of level, style, colour, and weight and the number of occurrences for each. The road and the stream networks were all present in one IGDS file, which also contained data on hydrological structures. All the layers and options that were entered during one IGDSARC conversion were converted to the same ARC/INFO coverage. The roads were in separate layers with respect to their class i.e. major or minor. All the layers which represented these roads were entered during one IGDSARC conversion and thus made up one ARC/INFO coverage representing the roads in the Abiaca watershed. The same process was carried out to create the stream network, shown in plate 1. Plates 2, 3 and 4 display the soil type, landuse, and DEM respectively.

Plate 1 : Stream Network

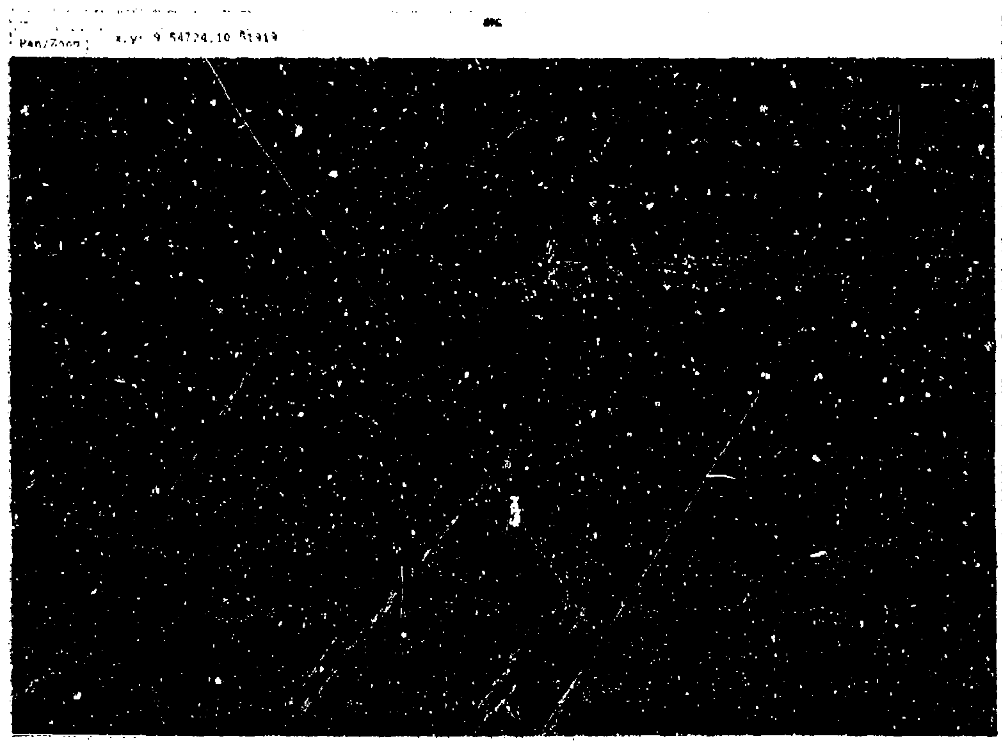


Plate 2 Soil (Channel Sediment) Coverage

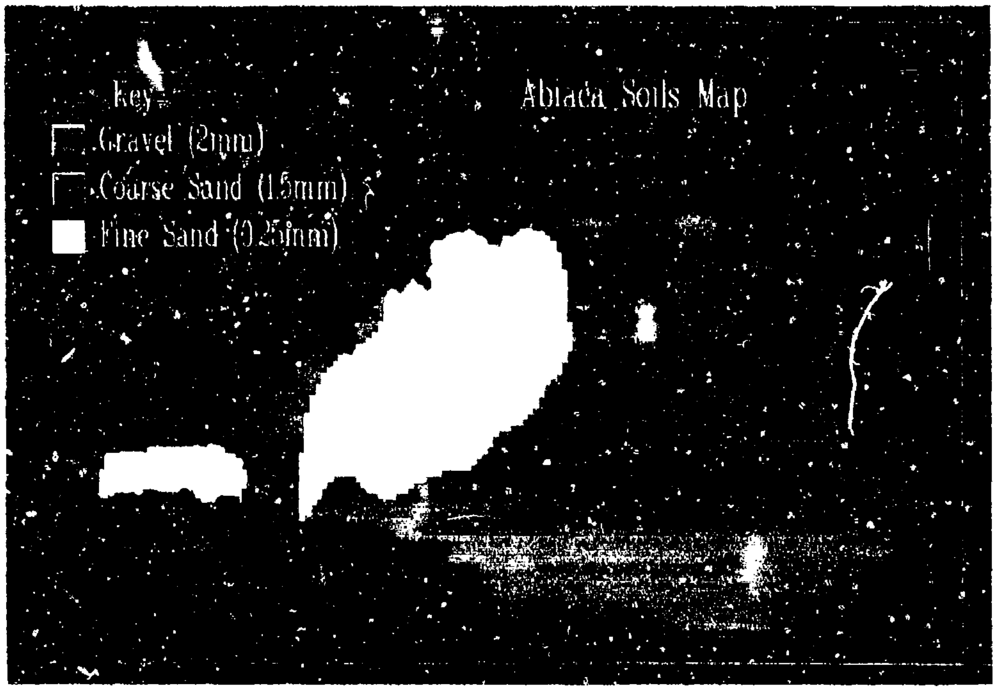


Plate 3 Landuse Coverage

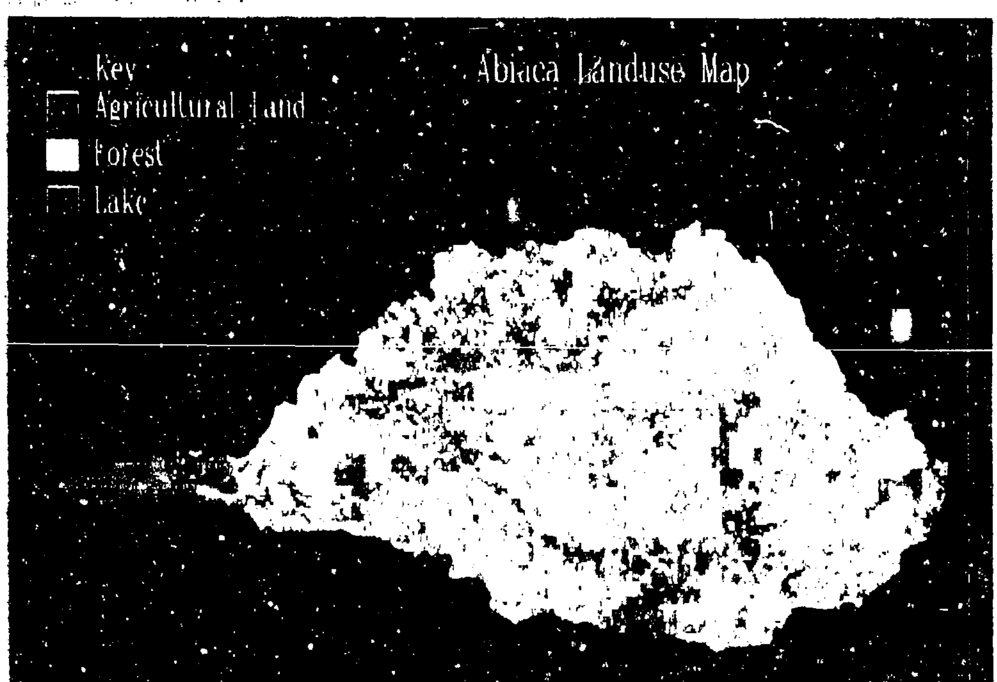


Plate 4 Digital terrain model

The roads which are in vector format are literally only a visual guide for indicating where on a stream a bridge occurs (an overlay of the two networks indicates a bridge at any intersection) These are potentially vulnerable areas when the debris build up is indicated causing possible failure of the bridges due to excessive stream bed scour. By carrying out the stream analysis upstream of the intersection point i e. a bridge, these bridge sites can be analysed

The stream network has been created from the DEM. It matched with the original digitally scanned vector network in general shape, the main channels being very much alike Far more minor tributaries were apparent in the derived network, although the vector network was scanned from a 1 100000 USGS map which would not have picked up these very small tributaries

The soil type map shows only three types of soil in the watershed These soil types are classified by their particle size which is the requirement for the Debris Management Support Program In the top two thirds of the watershed the soil type is of gravel composition with an average particle size of 2mm Following this zone is a band of fine sandy soil with particle size of 0 25 mm, followed by a narrow band of coarser sandy soil, particle size 1 5mm, then again a region of finer sandy soil before finishing with a small area of coarse sandy soil at the outlet of

the watershed. To compile the attributable information in the stream network, this grid was converted into a polygon coverage of five polygons.

The landuse map shows three types of landuse in the watershed. The small nose like extension from the main body of the watershed in the western region is almost entirely agricultural land; this is where the watershed reaches the end of the bluff and stretches out into the floodplain. The main body of the watershed is generally forest interspersed by agricultural land and small lakes. The original raster image contained twelve landuse types, forest, lakes and ten differing types of agricultural land. When this original image was converted to a polygon coverage, ARC/INFO was unable to complete the conversion because the polygons created exceeded 10,000 which is ARC/INFO's limit. The raster image was therefore reclassified, all agricultural types were classified as one type. The significant variable value in the DMP is whether the landuse is forested or not, different types of agricultural land are not distinguished and therefore one value was sufficient. The grid to polygon conversion then created a more manageable number of 1251 polygons.

The DEM is colour shaded based on elevation which enhances the readability of the map. It is very clearly shown where the flood plain gives way to the bluff, where the pale greens change to pale pinks. A marked feature of this map is the apparent visibility of the main drainage channels, beginning from the bluff line where the Abiaca Creek protrudes out into the flood plain.

1.5 Program Operation

Plate 5 shows the menu interface displaying the landuse map with the streams (in blue) and roads (in yellow) overlaid. This is achieved under the DRAW option on the menu title bar. This provides the user with the ability to carry out some visual interpretation such as identifying bridging points before they choose to analyse a specific area. When the ANALYSIS choice is selected on the menu title bar a ext box appears encouraging the user to zoom in on the area for analysis, because it is difficult to select an arc at such a small visual scale. When zooming in on an area, the user interactively drags out a small box around the chosen section, once the box is defined the screen clears and then redisplays the selected area as shown in Plate 6. After zooming in on the chosen section the user then selects the 'analyse streams' choice in the sub menu of the ANALYSIS option. The text box shown in Plate 6 explains to the user how to activate the analysis by placing the cross hairs onto the stream section of their choice. Once a choice is made a small box indicates the position and a text box is displayed which explains to the user to re-select the box and then press "9" to activate the watershed calculation. Further

text boxes are displayed after this if the selection process has been unsuccessful, i.e. the positioning of the selection point failed to select an arc, or the watershed area was far too low which would indicate that the selection point was not in the grid square of the stream channel on the DEM. Once this process has been completed the user activates the DMP by selecting RUN PROGRAM on the menu title bar. This activates processing in TABLES before activating the DMP through the TASK function. Once the DSP has processed the variables a results text box is automatically displayed on the screen (Plate 7).

Plate 5 Menu interface and coverages

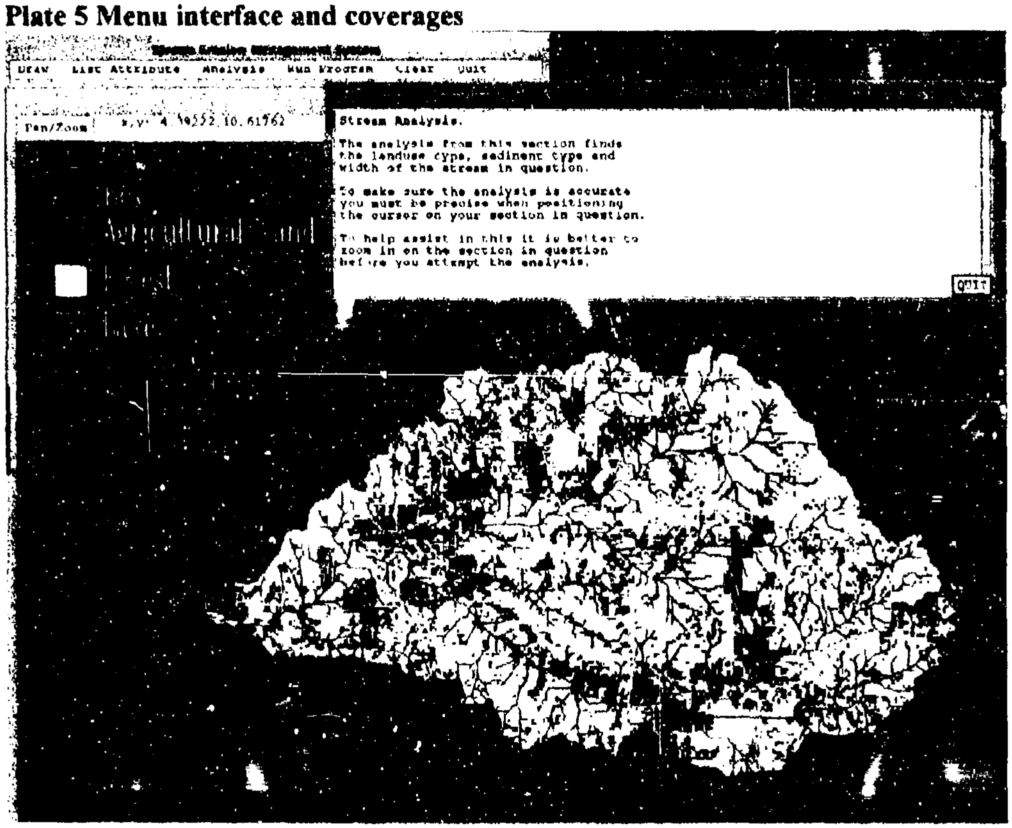


Plate 6 Selecting Analysis

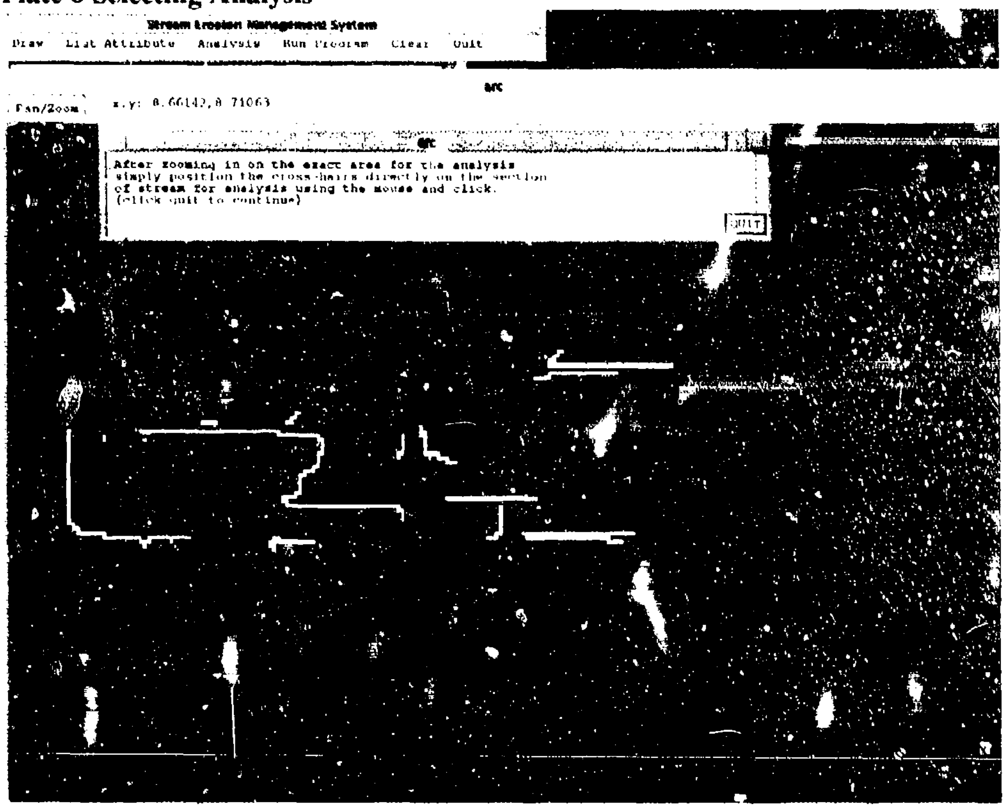
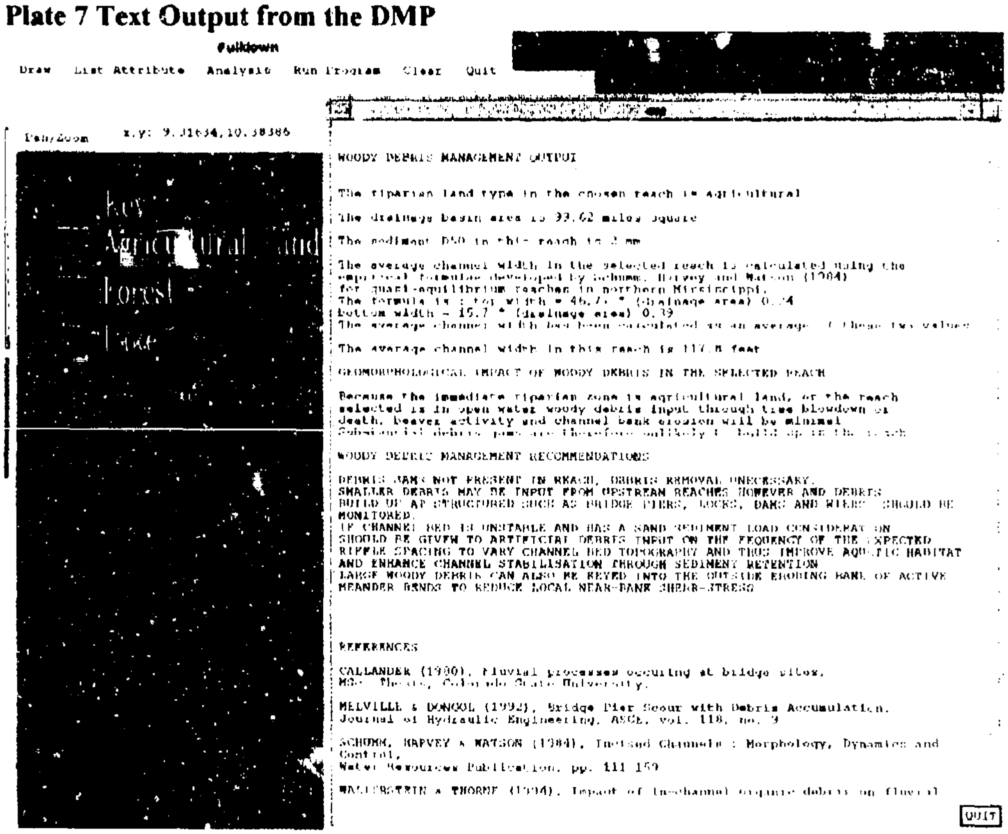


Plate 7 Text Output from the DMP



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APPENDIX B

Large Woody Debris Formation Survey used by Smith and Shields (1992)

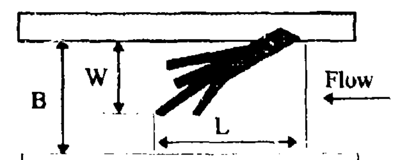
Stream Name ____________________

Reach Information ____________________

____

____

Date ______________ Time ______________

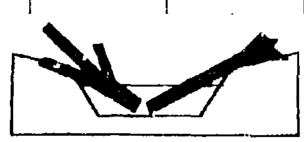


Dimensions

Width-Perpendicular to Flow Direction

	W<B/4	B/4<W<B/2	B/2<W<B
L<B/2			
B/2<L<B			
L>B			

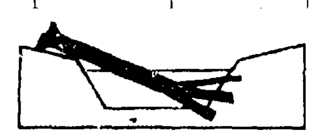
Length-Parallel to Flow Direction



TYPE A : COLLAPSED BRIDGE

Width-Perpendicular to Flow Direction

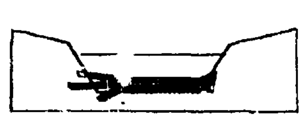
W<B/4	B/4<W<B/2	B/2<W<B



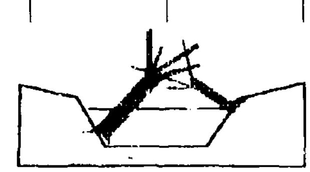
TYPE B : RAMP

L<B/2			
B/2<L<B			
L>B			

Length-Parallel to Flow Direction



TYPE C : DRIFT



TYPE D : STREAMBANK TREES

APPENDIX C

Method for predicting afflux due to LWD, developed by Gippel et. al. (1992)

The recommended procedure for predicting the hydraulic effect of managing large woody debris from a lowland river is as follows:

1) Measure the LWD:
   - projected length of LWD (L_*)
   - mean diameter of LWD in flow (d)
   - angle of orientation of the LWD in the flow (α)
2) Measure the channel morphology:
   - cross-sectional area of flow at selected discharge (A)
3) Measure or estimate flow characteristics at selected discharge:
   - depth of flow downstream of LWD (h_3)
   - 'ocity downstream of LWD (U_3)
4) Select a drag coefficient:
   - based on angle of orientation and snag form (C'_D) using Figure A1 or A2
5) Calculate the following:
   - Froude number downstream of LWD

     $$F = \frac{U_3}{\sqrt{gh_3}}$$

   - blockage ratio of LWD

     $B = L_* d / A$

   - drag coefficient corrected for blockage

     $C_D = C'_D(1-B)^{-3}$
6) Calculate afflux due to LWD:

   $$\Delta h = \frac{h_3\left[\left(F^2-1\right)+\sqrt{\left(F^2-1\right)^2+3C_D BF^2}\right]}{3}$$
7) Calculate the upstream extent of the afflux using a backwater procedure
8) Repeat the calculations for various management strategies such as lopping and rotation.

Figure 1 : Variation in drag coefficient with angle of rotation to the flow, measured for a model LWD complete with trunk, branches and butt, and for other combinations of these components

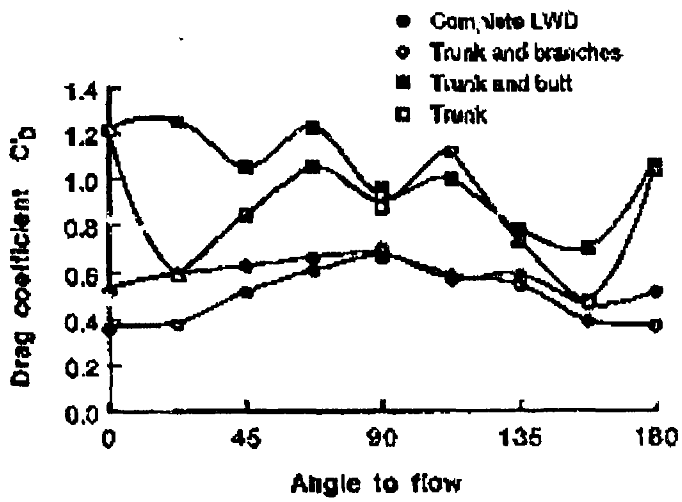
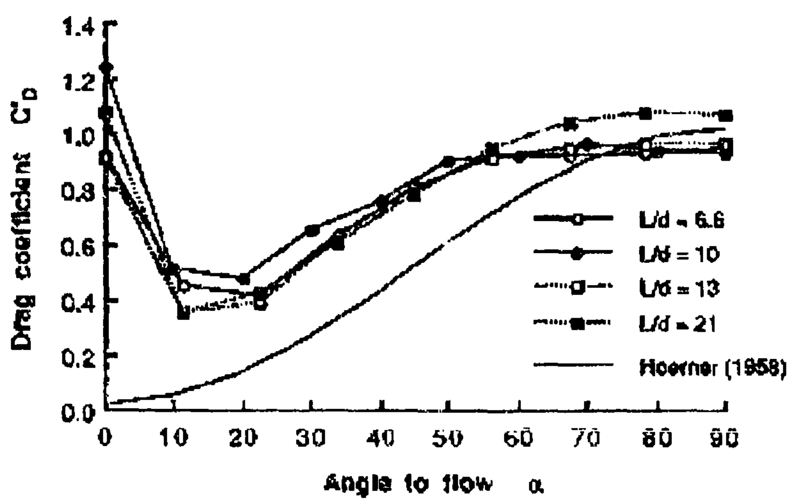


Figure 2 : Variation in drag coefficient with angle of rotation for cylinders of various lengths and diameters. Hoerner's (1958) relationship is for infinitely long cylinders.



APPENDIX D : FIELD DATA AND ANALYSIS CALCULATIONS

May 1995 Data

Creek	site (m)	No. Jams	Vol jams (m^3)	Flow Direction	Influence	Alpha Angle	Beta Angle	sinuosity	stage	sediment	Bar deposition (m^3)	Backwater Deposition (m^3)	Bed Scour (m^3)
Nalehoe	244		12 57	deflector	partial	90	10	straight	stage 2	sand/silt/gravel	25	0	0
	466		16 97	deflector	partial	90-180	20-30	straight	stage 2	sand/silt/gravel	0	0	0
	549		10 06	underflow	partial	90	20	straight	stage 2	sand/gravel	37 5	0	0
	671		9 1	deflector	partial	130	20	straight	stage 2	sand/gravel	0	25	0
	701 5		4 1	dam	partial	90	0	straight	stage 2	sand/gravel	0	0	0
	732		12 63	dam	partial	100	20	straight	stage 2	sand/gravel/clay	0	18	25
	762 5		10	deflector	partial	90-100	0	straight	stage 2	sand/gravel	0	0	0
	815	8	5 64	underflow	partial	90-180	30	straight	stage 2	sand/gravel	0	0	0
			total vol 81 09									total sed 105 5	total scour 25
Wortham west	30 5		5 68	dam-underflow	partial	90	5	sinuous	stage 2	sand	15	0	0
	152 5		0 47	underflow	partial	90	0	sinuous	stage 2	sand	0	0	0
	396 5		2 12	dam	partial	90	0	sinuous	stage 2	sand	0	25	1 2
	762 5		7 54	dam	partial	90	0	slightly sin	stage 2	sand	0	0	3 6
	1281		5 66	dam-underflow	partial	90	0	sinuous	stage 2	sand	10	0	0
	1525		6 35	deflector	partial	100	0	sinuous	stage 2	sand	0	0	4
	1738 5		1 96	dam	partial	90	0	slightly sin	stage 2	sand	0	0	0
	2135		2	beaver dam	complete	90	0	slightly sin	stage 2	sand	0	0	0
	2226 5		3	beaver dam	complete	90	0	slightly sin	stage 2	sand	0	0	0
	2501		2	beaver dam	complete	90	0	slightly sin	stage 2	sand	0	0	0
	3080 5		8 57	dam-underflow	partial	90	0	slightly sin	stage 2	sand	112 5	0	0
	3141 5	12	9 57	deflector	complete	90	0	sinuous	stage 2	sand	20	0	0
			total vol 54 9									total sed 182 5	total scour 8 8
Lee	381 25		1 41	dam	partial	90	0	straight	stage 4	sand	0	18	25
	564 25		2 82	dam	partial	90	0	straight	stage 4	sand	0	0	0
	732	3	1 41	underflow	partial	90	0	straight	stage 4	sand	0	0	0
			total vol 5 64									total sed 18	total scour 25
Perry	1098		2 82	underflow	partial	90	0	sinuous	stage 4	sand	0	0	0
	1220		15 03	underflow	partial	90	0	sinuous	stage 4	sand/gravel	0	0	0
	2165 5		10 06	dam	complete	180	0	sinuous	stage 3	sand	0	0	0
	2440		17 33	dam	partial	90	0	sinuous	stage 2	sand	0	0	0
	2668 75		7 06	dam	complete	90-180	0	slightly sin	stage 2	sand	0	0	0
	3050		5 03	underflow	partial	90	0	meandering	stage 2	sand	0	0	0
	3202 5	7	4 24	underflow	partial	90	0	sinuous	stage 1	sand	0	0	0
			total vol 61 57									total sed 0	total scour 0
Lick	1067 5		8 31	deflector	partial	90	0	straight	stage 2	clay/gravel	180	0	0
	1143 75	2	3	underflow	partial	90	0	straight	stage 2	clay/gravel	0	0	0
			total vol 11 31									total sed 180	total scour 0
Hickahala	305		17	deflector	partial	180	0	straight	stage 1	sand/clay	20 5	0	0
	396 5		30 11	deflector	complete	90	0	straight	stage 1	sand/clay	0	37 5	0
	915	3	27 29	dam	active	90	0	straight	stage 1	sand/clay	37 5	0	0
			total vol 74 4									total sed 97 5	total scour 0
Burney Branch	1235 25	1	6	deflector	partial	110	0	meandering	stage 5	sand	0	10	22
			total vol 6									total sed 10	total scour 22
Long	1159		10	parallel	partial	90-180	0	meandering	stage 2/3	sand	0	10	20
	1265 75		10	deflector	partial	100	0	meandering	stage 2/3	sand	0	10	20
	1357 25		5	beaver dam	active	90	0	meandering	stage 2/3	sand	0	20	0
	1586		5	parallel	partial	180	0	meandering	stage 2/3	sand	10	0	10
	1723 25		20	deflector	partial	90	0	meandering	stage 2/3	sand	20	0	15
	1967 25		4	beaver dam	active	90	0	straight	stage 2/3	clay	20	0	25
	2196		15	parallel	partial	170	0	straight	stage 2/3	clay	10	0	0
	2379		16	dam	active	90	0	straight	stage 2/3	clay	0	5	0
	2531 5		5	deflector	partial	120	0	straight	stage 2/3	sand	0	20	0
	2673		15	beaver dam	active	90	0	straight	stage 2/3	sand	0	5	10
	2745		21	parallel	partial	180	0	straight	stage 2/3	clay	30	10	20
	3172		20	parallel	partial	180	0	straight	stage 2/3	clay	50	20	20
			total vol 146									total sed 140	total scour 140
Sykes	0		11 63	parallel	partial	180	0	meandering	stage 3	sand	32	0	10
	228 75		45	parallel	partial	180	0	meandering	stage 3	sand	25	0	0
	335 5		80	deflector	partial	180	0	meandering	stage 3	sand	0	0	0
	930 25		18 5	deflector	partial	140	0	meandering	stage 3	sand	0	0	0
	1021 75		12	deflector	partial	180	0	meandering	stage 3	sand	0	0	0
	1159		36	deflector	partial	180	0	meandering	stage 3	sand	0	0	0
	1296 25		12	dam	partial	90	0	meandering	stage 3	sand	12	30	15
	1357 25	6	5	deflector	partial	90	0	meandering	stage 3	sand	20	60	0
			total vol 200									total sed 179	total scour 25
Fartleguaha	329 4		5	deflector	partial	90	0	straight	stage 2/3	sand/gravel	100	0	20
	610		5	deflector	partial	90	0	straight	stage 2/3	sand/gravel	15	0	10
	1296 25	3	30	dam-underflow	partial	90	0	straight	stage 2/3	sand/gravel	15	0	10
			total vol 40									total sed 130	total scour 40
Abiaca 1	137 25		8 81	dam	partial	90	0	slightly sin	stage 4	sand	0	2 5	0
	183		0 75	dam	partial	90	0	slightly sin	stage 4	sand	10	0	2
	274 5		6 36	deflector	partial	90	0 20	slightly sin	stage 4	sand	0	0	0
	366		13 15	dam/deflector	partial	90 130	0	meandering	stage 4	sand	168	0	10
	884 5		8 48	deflector	partial	90	10	meandering	stage 4	sand	36	40	24
	1159	6	3 39	dam	active	90	0	meandering	stage 4	sand	0	0	0
			total vol 40 99									total sed 254	total scour [illegible]
Harland	152 5		5 29	parallel	partial	180	0	meandering	stage 2/3	sand/gravel	0	0	0 25
	555 1		9 08	dam	complete	90	0	meandering	stage 2/3	sand/gravel	0	25	15
	811 1		13 42	deflector	complete	90 180	0	slightly sin	stage 2/3	sand/gravel	120	100	25
	975		8 83	parallel	partial	180	0	slightly sin	stage 2/3	sand/gravel	37 5	0	0
	1067 5		8 47	parallel	partial	180	0	meandering	stage 2/3	sand/gravel	50	0	0
	1174 25		14 12	parallel	complete	90	0	meandering	stage 2/3	sand/gravel	0	0	0
	1281		10 37	parallel	partial	180	0	meandering	stage 2/3	sand/gravel	187 5	60	
	1341	8	3 77	parallel	partial	180	0	meandering	stage 2/3	sand/gravel	0	0	240
			total vol 73 35									total sed 580	total scour 280 25
Otoucalofa	76 25		6	parallel	partial	180	0	meandering	stage 3	sand	6	0	25
	228 75		20	parallel	partial	180	0	meandering	stage 3	sand	50	0	0
	237 9		8	parallel	partial	180	0	meandering	stage 3	sand	20	0	25
	366		12	parallel	partial	120	0	straight	stage 3	sand	0	0	5
	457 5		11	parallel	partial	180	0	meandering	stage 3	sand	10	0	2
	579 5		14	parallel	partial	180	0	meandering	stage 3	sand	0	0	50
	768 6		9	parallel	partial	180	0	sinuous	stage 3	sand	0	0	20
	915		24	parallel	partial	180	0	sinuous	stage 3	sand	0	0	10
	1067 5	9	15	parallel	partial	180	0	sinuous	stage 3	sand	0	0	25
			total vol 119									total sed 86	total scour [illegible]
[illegible]	0		15	parallel	partial	180	0	meandering	stage 5	sand/gravel	300	0	75
	335 5		24 8	parallel	partial	180	0	meandering	stage 5	sand/gravel	60	0	0
	503 25		5 6	parallel	partial	170	0	meandering	stage 5	sand/gravel	250	0	0
	610		4 9	parallel	partial	[illegible]	0	slightly sin	stage 5	sand/gravel	0	0	0
	808 25		1	parallel	partial	[illegible]	0	slightly sin	stage 5	sand/gravel	0	0	0
	1052 25		4	underflow	partial	90	0	meandering	stage 5	sand/gravel	0	0	0
	1189 5		1 5	underflow	partial	90	0	straight	stage 5	sand/gravel	30	0	0
			total vol 43 3									total sed 640	total scour 75
Abiaca 4	329 4		30	parallel	partial	180	0	meandering	stage 4/5	sand/gravel	0	67 5	0
	793	2	100	parallel	partial	180	10	meandering	stage 4/5	sand/gravel	315	0	100
			total vol 130									total sed 382 5	total scour 100
Harland 23	0		17 5	parallel	partial	180	0	meandering	stage 5	sand/gravel	0	0	10
	396 5		10	parallel	partial	180	0	meandering	stage 5	sand/gravel	0	0	10
	488		10	parallel	partial	180	0	meandering	stage 5	sand/gravel	0	0	5
	610		9	parallel	partial	180	0	meandering	stage 5	sand/gravel	20	0	5
	1098		35	parallel	partial	180	0	meandering	stage 5	sand/gravel	10	0	0
	1220		9	parallel	partial	180	0	meandering	stage 5	sand/gravel	20	0	0
	1372 5	7	16	parallel	partial	180	0	meandering	stage 5	sand/gravel	0	0	0
			total vol 127									total sed 50	total scour 32
Abiaca 5	366	1	2 51	parallel	partial	180	0	meandering	stage 5	sand/gravel	60	0	0
			total vol 2 51									total sed 60	total scour 0

May 1996 Data

Data May 1996 Creek	site (m)	No. Jams	Vol jams (m^3)	Flow Direction	Influence	Alpha Angle	Beta Angle	sinuosity	stage	sediment	Bar deposition (m^3)	Backwater Deposition (m^3)	Bed Scour (m^3)
Nolehoe	244		30	deflector	partial	90-110	10	straight	stage 2	sand/silt/gravel	35	0	0
	488		18.97	deflector	partial	90-180	20-30	straight	stage 2	sand/silt/gravel	0	0	20
	549		25.5	underflow	partial	90	20	straight	stage 2	sand/gravel	37.5	0	0
	671		10	deflector	partial	90	20	straight	stage 2	sand/gravel	0	25	0
	701.5		5	dam	partial	130	0	straight	stage 2	sand/gravel	0	0	0
	732		15	dam	partial	120	20	straight	stage 2	sand/gravel/clay	60	18	25
	762.5		10	deflector	partial	90-120	0	straight	stage 2	sand/gravel	25	0	0
new	823.5		15	underflow	partial	90	0	straight	stage 2	sand/gravel	0	0	0
new	854		10	underflow	partial	90	0	straight	stage 2	sand/gravel	0	0	0
	915	10	21	underflow	partial	90-180	30	straight	stage 2	sand/gravel	0	0	0
			total vol 158.5									total sed. 180.5	total scour 45
Worsham	30.5		6	dam-underflow	partial	90	5	sinuous	stage 2	sand	15	0	0
west	152.5		2	dam	partial	90	0	sinuous	stage 2	sand	0	0	0
	366.5		5	dam	partial	90	0	sinuous	stage 2	sand	0	25	1.2
	762.5		6	dam	partial	90	0	slightly sinuous	stage 2	sand	0	0	3.6
	1281		5.56	dam-underflow	partial	90	0	sinuous	stage 2	sand	10	0	0
	1525		6.35	deflector	partial	100	0	sinuous	stage 2	sand	0	0	4
new	1677.5		10	dam	partial	90	0	sinuous	stage 2	sand	0	0	0
	1738.5		5	dam	partial	90	0	slightly sinuous	stage 2	sand	0	0	0
destroyed	2135												
	2226.5		3	beaver dam	complete	90	0	slightly sinuous	stage 2	sand	0	80	0
new	2257		3	beaver dam	active	90	0	sinuous	stage 2	sand	0	80	
	2501		2	beaver dam	complete	90	0	slightly sinuous	stage 2	sand	0	80	0
	3080.5		11	dam-underflow	partial	90	0	slightly sinuous	stage 2	sand	112.5	0	0
	3141.5	13	9.57	deflector	complete	90	0	sinuous	stage 2	sand	20	0	0
			total vol 76.6									total sed. 362.5	total scour 4.8
[illegible]	381.25		1.41	dam	partial	90	0	straight	stage 5	sand	0	18	25
[illegible]	584.25												
	732	2	1.41	underflow	partial	90	0	straight	stage 5	sand	0	0	0
			total vol 2.82									total sed. 18	total scour 25
Perry	1098		3	underflow	partial	90	0	sinuous	stage 4	sand	0	20	0
	1220		20.5	underflow	partial	90	0	sinuous	stage 4	sand/gravel	0	0	0
	2165.5		10.06	dam	complete	180	0	sinuous	stage 3	sand	5	0	10
	2440		17.33	dam	partial	90	0	sinuous	stage 2	sand	25	12.5	0
	2664.75		7.06	dam	complete	90-180	0	slightly sinuous	stage 2	sand	0	0	0
	3050		5.03	underflow	partial	90	0	meandering	stage 2	sand	30	10	30
	3202.5	7	4.24	underflow	partial	90	0	sinuous	stage 1	sand	0	25	0
			total vol 67.22									total sed. 127.5	total scour 30
Lick	1067.5		8.31	deflector	partial	90	0	straight	stage 2	clay/gravel	130	0	0
removed	1143.75	1											
			total vol 8.31									total sed. 130	total scour 0
Hickahala	305		17	deflector	partial	180	0	straight	stage 1	sand/clay	20.5	0	45
	396.5		30.11	dam	complete	90	0	straight	stage 1	sand/clay	0	37.5	10
	915	3	27.29	dam	active	90	0	straight	stage 1	sand/clay	37.5	0	0
			total 74.4									total sed. 97.5	total scour 55
Burney Branch	1235.25	1	7.5	deflector	partial	110	0	meandering	stage 5	sand	0	20	13
			total vol 7.5									total sed. 20	total scour 13
Long	1159		10	parallel	partial	90-180	0	meandering	stage 2/3	sand	0	10	20
	1265.75		10	deflector	partial	100	0	meandering	stage 2/3	sand	0	10	20
	1357.25		5	beaver dam	active	90	0	meandering	stage 2/3	sand	0	20	0
	1586		5	parallel	partial	180	0	meandering	stage 2/3	sand	10	0	10
	1723.25		20	deflector	partial	90	0	meandering	stage 2/3	sand	20	0	15
	1967.25		4	beaver dam	active	90	0	straight	stage 2/3	clay	20	0	25
	2196		15	parallel	partial	170	0	straight	stage 2/3	clay	10	0	0
	2379		16	dam	active	90	0	straight	stage 2/3	clay	0	5	0
	2531.5		5	deflector	partial	120	0	straight	stage 2/3	sand	0	20	0
	2623		15	beaver dam	active	90	0	straight	stage 2/3	sand	0	5	10
	2745		21	parallel	partial	180	0	straight	stage 2/3	clay	30	10	20
	3172	12	20	parallel	partial	180	0	straight	stage 2/3	clay	50	20	20
			total 146								total sed. 140		total scour 140
Sykes	0		11.63	parallel	partial	180	0	meandering	stage 3	sand	32	0	15
	228.75		45	parallel	partial	180	0	meandering	stage 3	sand	25	0	0
	[illegible]		60	deflector	partial	180	0	meandering	stage 3	sand	0	0	30
destroyed	[illegible]												
	1021.75		17	deflector	partial	180	0	meandering	stage 3	sand	0	0	0
	1159		36	deflector	partial	180	0	meandering	stage 3	sand	0	0	0
	1296.25		12	dam	partial	90	0	meandering	stage 3	sand	12	30	0
	1357.25	7	5	deflector	partial	90	0	meandering	stage 3	sand	20	60	35
			total vol 181.63								total sed. 179		total scour 80
Fannegusha	329.4		5	deflector	partial	90	0	straight	stage 2/3	sand/gravel	100	0	20
	610		5	deflector	partial	90	0	straight	stage 2/3	sand/gravel	15	0	10
	1296.25	3	30	dam-underflow	partial	90	0	straight	stage 2/3	sand/gravel	15	0	10
			total vol 40								total sed. 130		total scour 40
Abiaca 1	137.25		8.83	dam	partial	90	0	slightly sinuous	stage 4	sand	0	5	0
	183		1.5	dam	partial	100	0	slightly sinuous	stage 4	sand	10	0	2
	274.5		10	deflector	partial	90	0.20	slightly sinuous	stage 4	sand	0	0	2
	366		13.15	dam/deflector	partial	90-130	0	meandering	stage 4	sand	125	0	10
	884.5		12	deflector	partial	90	10	meandering	stage 4	sand	36	25	15
	1159		3.39	dam	active	90	0	meandering	stage 4	sand	0	0	0
new	1281	7	20	deflector	partial	120	0	meandering	stage 4	sand	0	0	4
			total vol 68.87								total sed. 201		total scour 31
Harland	152.5		6.5	parallel	partial	180	0	meandering	stage 2/3	sand/gravel	0	0	0.25
	555.1		10.3	dam	complete	90	0	meandering	stage 2/3	sand/gravel	0	25	15
	811.3		13.42	deflector	complete	90-180	0	slightly sinuous	stage 2/3	sand/gravel	85	100	25
	976		8	parallel	partial	180	0	slightly sinuous	stage 2/3	sand/gravel	37.5	0	0
	1067.5		8.5	parallel	partial	180	0	meandering	stage 2/3	sand/gravel	50	0	0
	1174.25		14.12	parallel	complete	90	0	meandering	stage 2/3	sand/gravel	0	0	0
	1281		10.37	parallel	partial	180	0	meandering	stage 2/3	sand/gravel	187.5	80	
	1342	8	3.5	parallel	partial	180	0	meandering	stage 2/3	sand/gravel	0	0	120
			total vol 74.9								total sed. 545		total scour 160.25
Otoucalofa	76.25		5	parallel	partial	180	0	meandering	stage 2	sand	8	0	3.5
	228.75		20	parallel	partial	180	0	meandering	stage 2	sand	40	0	0
	317.9		8	parallel	partial	180	0	meandering	stage 2	sand	15	0	2.5
	366		12	parallel	partial	180	0	straight	stage 2	sand	0	0	5
	457.5		11	parallel	partial	180	0	meandering	stage 2	sand	10	0	2
	579.5		14	parallel	partial	180	0	meandering	stage 2	sand	0	0	50
	768.6		9	parallel	partial	180	0	sinuous	stage 2	sand	0	0	20
	91.5		24	parallel	partial	180	0	sinuous	stage 2	sand	0	0	10
	1067.5	9	15	parallel	partial	180	0	sinuous	stage 2	sand	0	0	2.5
			total vol 119								total sed. 73		total scour 95.5
Coila	0		5	parallel	partial	180	0	meandering	stage 4	sand/gravel	150	0	75
	335.5		35	parallel	partial	180	0	meandering	stage 4	sand/gravel	80	0	0
	503.25		5.6	parallel	partial	180	0	meandering	stage 4	sand/gravel	200	0	0
	610		4.9	parallel	partial	180	0	slightly sinuous	stage 4	sand/gravel	20	0	0
	808.25		3	parallel	partial	180	0	slightly sinuous	stage 4	sand/gravel	0	0	0
	1052.25		2	underflow	partial	90	0	meandering	stage 4	sand/gravel	0	0	0
	1189.5	7	1	underflow	partial	90	0	straight	stage 4	sand/gravel	30	0	0
			total vol 56.5								total sed. 480		total scour 75
Abiaca 4	329.4		30	parallel	partial	180	0	meandering	stage 4/5	sand/gravel	0	67.5	0
	793	2	100	parallel	partial	180	10	meandering	stage 4/5	sand/gravel	250	0	80
			total vol 130								total sed. 317.5		total scour 80
Harland 2/3	0		37.5	parallel	partial	180	0	meandering	stage 4	sand/gravel	0	0	10
	396.5		15	parallel	partial	180	0	meandering	stage 4	sand/gravel	0	0	10
	488		15	parallel	partial	180	0	meandering	stage 4	sand/gravel	20	0	6
	610		12	parallel	partial	180	0	meandering	stage 4	sand/gravel	20	0	6
	1098		35	parallel	partial	180	0	meandering	stage 4	sand/gravel	10	0	6
	1220		12	parallel	partial	180	0	meandering	stage 4	sand/gravel	20	0	0
	1372.5	7	24	parallel	partial	180	0	meandering	stage 4	sand/gravel	0	0	0
			total vol 150.5								total sed. 80		total scour 38
Abiaca 8	366		5	parallel	partial	180	0	meandering	stage 5	sand/gravel	35	0	0
new	533.75	2	20	parallel	partial	180	0	meandering	stage 5	sand/gravel	15	0	0
			total vol 25								total sed. 50		total scour 0

creek	drainage a	composite	stream po	reach lengt	total no jar	av. no per	total vol de	av. vol. pe	total vol. s	av vol per	total vol se	av. vol per	net sed. b	av. spacin	sinuosity
nolehoe	9.5	11.1	170	1220	10	0.6557	158.5	12.9918	180.5	14.79508	45	3.638524	11.10656	108.58	1
worsham	10.3	11.4	58.4	3050	13	0.4262	76.6	2.511475	362.5	11.88525	4.8	0.157377	11.72787	259.25	1.2
lee	19.4	32.8	19.2	1372.5	2	0.1457	2.82	0.205465	18	1.311475	25	1.821494	-0.51002	350.75	1.3
perry	20.9	21.4	60.5	3355	7	0.2086	67.22	2.003577	127.5	3.800298	30	0.894188	2.90611	350.75	1.3
lick	22	14.9 ?		1220	1	0.08197	8.31	0.681148	130	10.65574	0	0	10.65574	1067.5	1.2
nickanala	23.3	13.6	88.3	1372.5	3	0.2186	74.4	5.420765	97.5	7.103825	13	0.947177	6.156649	305	1.3
burney br	25.9	31.8 ?		1830	1	0.05464	7.5	0.409836	20	1.092896	55	3.005465	-1.91257	1235.25	1.3
long	28.7	18	67.5	3202.5	12	0.3747	146	4.558939	140	4.371585	140	4.371585	0	188.49	1.3
sykes	31.5	24.6	43	1220	7	0.5738	181.63	14.8877	179	14.67213	80	6.557377	8.114754	225.09	1.4
fannegusi	46.6	22.5	82	1220	3	0.2459	40	3.278688	130	10.65574	40	3.278688	7.377049	483.425	1
abiaca 3	58.6	17	51	1372.5	7	0.51	68.87	5.017851	201	14.64481	33	2.404372	12.24044	190.625	1.7
harland 1	69.9	26	32.4	1372.5	8	0.5829	74.9	5.457195	545	39.70856	160	11.65756	28.051	169.885	1.7
otoucalofa	106.2	27.2	51.7	1220	9	0.7377	119	9.754098	73	5.983606	95	7.786885	-1.80328	123.83	1.5
cola	108.8	17.4	145	1372.5	7	0.51	56.5	4.116576	460	33.51548	75	5.464481	28.051	198.25	1.4
abiaca 4	114	21.4	78.6	1372.5	2	0.1457	130	9.471766	317.5	23.13297	80	5.82878	17.30419	463.6	1.7
harland 23	130 ?	?		1830	7	0.3825	150.5	8.224044	60	3.278688	38	2.076503	1.202186	228.75	1.5
abiaca 6	256.4	31.7	38.5	1372.5	2	0.1457	25	1.821494	50	3.642987	0	0	3.642987	167.75	1.4

creek	drainage a	KM^2	composite	width (m)	composite	depth (m)	composite	sediment t	sed. trans	2yr Q(cfs)	2yr Q (cun	da (sq. km	2yr Q (cur	da (sq. km	power / wi	composite	2yr Q(cfs)	AGI	width (m)	depth (m)
Harland	27	69.93	85.2	25.986	5.88	1.7934	0.00081	35.08	34.51672	3739	105.8137	69.93	105.8137	69.93	32.35612	0.00081	3739	3.02859	25.986	1.7934
Fannegus	18	46.62	73.8	22.509	7.39	2.25395	0.002	28640	28181.76	3325	94.0975	46.62	94.0975	46.62	82.02021	0.002	3325	6.65	22.509	2.25395
Abiaca 3	26.5	68.635	55.9	17.0495	6.5	1.9825	0.00094	7602	7480.368	3339	94.4937	68.635	94.4937	68.635	51.1079	0.00094	3339	3.13866	17.0495	1.9825
Abiaca 4	44	113.96	70	21.35	3.2	0.976	0.0016	1925	1894.2	3780	106.974	113.96	106.974	113.96	78.64468	0.0016	3780	6.048	21.35	0.976
Coila	42	108.78	57	17.385	3.2	0.976	0.0019	34	33.456	4780	135.274	108.78	135.274	108.78	145.0315	0.0019	4780	9.082	17.385	0.976
Abiaca 6	99	256.41	104	31.72	5.7	1.7385	0.00062	1831	1801.704	7095	200.7885	256.41	200.7885	256.41	38.5005	0.00062	7095	4.3989	31.72	1.7385
nolehoe	3.7	9.583	36.65	11.17825	4.1	1.2505	0.007	1053	1036.152	978	27.6774	9.583	27.6774	9.583	170.0273	0.007	978	6.846	11.17825	1.2505
lick	8.5	22.015	49	14.945	5.41	1.65005	0.0027	11566	11330.94		0	72.002	111.8133	72.002	54.94432	0.0027 ?		?	14.945	1.65005
Red Bank	27.8	72.002	108	32.94	6.3	1.9215	0.00165	2518	2477.712	3951	111.8133	19.425	38.9691	19.425	19.23823	0.00165	3951	6.51915	32.94	1.9215
Lee	7.5	19.425	107.5	32.7875	6.3	1.9215	0.00165	25185	24782.04	1377	38.9691	23.31	61.0714	23.31	88.28299	0.00165	1377	2.27205	32.7875	1.9215
Hickahala	9	23.31	44.5	13.5725	5.3	1.6165	0.002	10455	10287.72	2158	61.0714	44.289	95.8238	44.289	85.74539	0.002	2158	4.316	13.5725	1.6165
Burney Br	10	25.9	104.3	31.8115	7.2	2.196	0.00087	4057	3992.088		0	13.986	33.394	13.986	8.774195	0.00087 ?		?	31.8115	2.196
Lower Hot	17.1	44.289	64.7	19.7335	12.7	3.8735	0.0018	45161	44438.43	3366	95.8238	12.173	33.677	12.173	69.65047	0.0018	3366	6.0948	19.7335	3.8735
Upper Hot	5.4	13.986	71	21.655	5.3	1.6165	0.00058	1249	1229.016	1180	33.394	106.19	130.6611	106.19	51.70954	0.00058	1180	0.6844	21.655	1.6165
Marcum	4.7	12.173	45.1	13.7555	4.4	1.342	0.0029	19589	19275.58	1190	33.677	16.576	39.3653	16.576	78.31812	0.0029	1190	3.451	13.7555	1.342
Otoucalofa	41	106.19	83.4	27.267	8.55	2.60775	0.0011	27278	26841.55	4617	130.6611	20.979	50.657	20.979	60.51791	0.0011	4617	5.0787	27.267	2.60775
Sarter	6.4	16.576	38.8	11.834	5	1.525	0.0024	8111	7981.224	1391	39.3653	31.598	71.9386	31.598	42.95473	0.0024	1391	3.3384	11.834	1.525
Perry	8.1	20.979	70	21.35	6.3	1.9215	0.0026	11095	10917.48	1790	50.657	24.605	54.7605	24.605	71.48439	0.0026	1790	4.654	21.35	1.9215
Sykes	12.2	31.598	80.8	24.644	5.49	1.67445	0.0015	24197	23809.85	2542	71.9386	13.468	32.6299	13.468	30.59098	0.0015	2542	3.813	24.644	1.67445
East Wors	9.5	24.605	56.67	17.28435	6.15	1.87575	0.0023	20005	19684.92	1935	54.7605	10.36	31.0168	10.36	58.37152	0.0023	1935	4.4505	17.28435	1.87575
Middle Wo	5.2	13.468	44.6	13.603	5.05	1.54025	0.0013	9738	9582.192	1153	32.6299	27.972	61.9487	27.972	47.60272	0.0013	1153	1.4989	13.603	1.54025
West Wor	4	10.36	37.6	11.468	4.8	1.464	0.0022	9173	9026.232	1096	31.0168	28.749	62.5147	28.749	67.47836	0.0022	1096	2.4112	11.468	1.464
James Wo	10.8	27.972	73.25	22.34125	6	1.83	0.00175	10685	10514.04	2189	61.9487					0.00175	2189	3.83075	22.34125	1.83
Long	11.1	28.749	59	17.995	3.9	1.1895	0.00198	5382	5295.888	2209	62.5147					0.00198	2209	4.37382	17.995	1.1895